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PUBLIC HEALTH EVALUATION
PROJECT RULISON
(PRODUCTION TESTING)

MASTER

by
Roy B. Evans
David E. Bernhardt
Programs and Plans
Southwestern Radiological Health Laboratory

U.S. Department of Health, Education and Welfare
Public Health Service
Environmental Health Service
Environmental Control Administration
Bureau of Radiological Health

May 1970
Second Printing - August 1970

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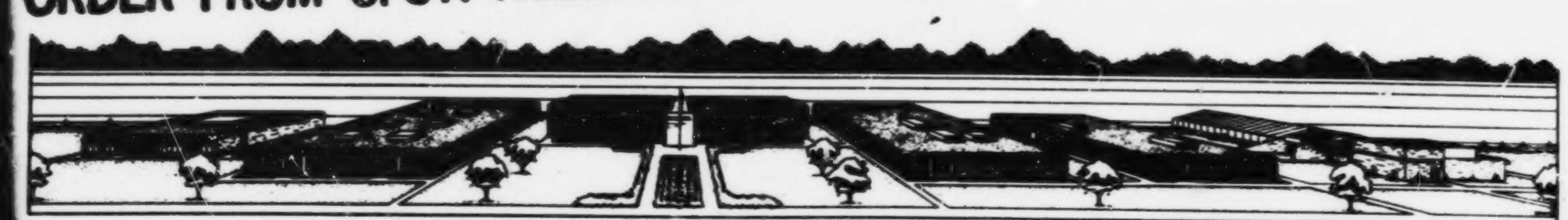

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ABSTRACT

Project Rulison is a Plowshare experiment to investigate the feasibility of nuclear explosive stimulation of natural gas production. The detonation of the explosive took place on September 10, 1969. Production testing activities will be initiated six months or more after the detonation and will entail flaring of natural gas containing radioactivity. The radionuclides of primary interest which will be released by production testing are tritium and krypton-85.

This report presents an analysis of the public health implications of the radioactivity releases associated with Project Rulison production testing. Concentrations and possible movement of radionuclides in ground water near the chimney are estimated, and potential human doses from radioactivity released to the atmosphere during production testing are postulated.

The analysis presented indicates that Project Rulison production testing operations can be conducted well within the radiological safety guides of the Federal Radiation Council and Atomic Energy Commission. The postulated dose to members of the public is on the order of one-tenth mrem.

FOREWORD

PLOWSHARE

The mission of the Plowshare program is to develop technology for the peaceful use of nuclear explosives for the benefit of man. Plowshare is attempting to obtain additional return from national resources expended in developing nuclear weapons. Benefits can be derived from the peaceful application of nuclear explosives, but risks from radioactivity and other detonation effects are inherently associated with such applications. Nuclear explosives, like any other engineering tool, must be shown to yield benefits that outweigh the costs and risks involved.

PUBLIC HEALTH EVALUATION OF PLOWSHARE PROJECTS

In July of 1969, a project was initiated at the Southwestern Radiological Health Laboratory (SWRHL) in Las Vegas, Nevada, to evaluate public health aspects of peaceful applications of nuclear explosives. The SWRHL, under a Memorandum of Understanding between the Atomic Energy Commission (AEC) and the U. S. Public Health Service (PHS), conducts the off-site radiological safety program for nuclear tests. Although this project to evaluate health aspects of peaceful applications of nuclear explosives uses competency developed through work performed under the AEC-Memorandum of Understanding, the project is separate from that endeavor and is solely a PHS function.

The purpose of this effort is to identify and evaluate the radiological health implications of Plowshare projects. The intent is to review and summarize the AEC safety evaluations and to supplement them if necessary. If such AEC evaluations are not available on a timely basis, independent evaluations will be performed using preliminary information.

The AEC safety evaluation, NVO-61 (38), "Project Rulison Post-Shot Plans and Evaluations," was not released until December 1969. This report was written prior to release of NVO-61. Pertinent parameters from NVO-61 are summarized in Appendix H for comparison with those used in this report. Differences between parameters used in NVO-61 and parameters used here do not change the conclusions of this report.

SUMMARY AND CONCLUSIONS

This report uses preliminary information available to the public to analyze the public health implications of Project Rulison. Concentrations and possible movement of radionuclides in ground water near the chimney are estimated, and environmental levels of radionuclides and doses to humans resulting from radioactivity released to the atmosphere from production testing are hypothesized.

The following summarizes the estimated environmental effects:

1. Contaminated ground water is not expected to migrate away from the chimney during gas production since gas inflow will tend to inhibit radionuclide migration. When movement occurs, it will be so slow as to allow decay to concentrations below the radiation protection guides (39) within a fraction of a mile.

2. The only radionuclides expected to be present in detectable quantities in flared gas during production testing are tritium and krypton-85. The average airborne concentrations are expected to be three or more orders of magnitude below the concentration guides for the general population at the nearest populated locations (three miles from the site).

3. Tritium concentrations in vegetation moisture at locations a few miles away may range up to several hundred pCi/ml of water and concentrations in milk to several tens of pCi/ml.

The postulated dose to members of the public is on the order of one-tenth millirem. The doses resulting from ingestion of foodstuffs (milk, vegetables, etc.) may be an order of magnitude or more above doses from inhalation or drinking water. The chronic dose, due to the residual tritium in the environment after the peak production testing phase, is estimated to be an order of magnitude greater than the acute dose during the three-week test period.

The analysis presented in this paper indicates that the Project Rulison production testing operation can be conducted well within the radiological guides of the FRC and the AEC standards. In addition, the environmental surveillance program proposed by the SWRHL should be capable of detecting levels of environmental radioactivity well below the guides. This surveillance program will provide information to initiate necessary protective actions should unexpected circumstances occur. The use of surveillance data to detect the need for protective action will require timely analysis and reporting of results.

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I. INTRODUCTION

Project Rulison is the second of a series of Plowshare experiments to investigate the feasibility and develop the technology for nuclear explosive stimulation of natural gas production. Several gas fields in the U. S. contain large reserves which cannot be economically recovered with conventional well-completion technology because the gas-bearing formations are of relatively low permeability. Several methods have been used in attempts to stimulate gas production in these low permeability regions, including hydraulic fracturing, fracturing with conventional explosives, and the use of chemicals to increase formation permeability. These stimulation techniques have met with varying degrees of success and have contributed significantly to usable national reserves of natural gas. However, gas in a number of reservoirs in Colorado and neighboring states (see Appendix A) cannot be recovered economically with conventional stimulation techniques, and nuclear stimulation is being investigated for possible use in these reservoirs.

Nuclear stimulation, like stimulation with conventional explosives, is intended to increase the effective well diameter by fracturing the gas-bearing formation in the vicinity of the drill hole. Since a nuclear device is capable of releasing much more energy than a conventional device of comparable physical size, the nuclear explosive can produce a much larger effective well radius than is obtainable with a conventional explosive. Gas deliverability should increase as the effective well radius increases.

Concepts involved in the engineering use of nuclear explosives are largely based on experience with underground nuclear testing at the Nevada Test Site. Safety programs for this testing have been described in references 1, 2, and 3.

In Project Gasbuggy, the first nuclear gas stimulation experiment, a 29-kt explosive was detonated 4,240 feet below the surface of the Carson National Forest in New Mexico on December 10, 1967.* The objective of this joint government-industry experiment (sponsors were the Atomic Energy Commission, Department of the Interior, and the El Paso Natural Gas Company) was to examine the general feasibility of the technique and to provide an indication of possible problems which might result from the radioactivity in the gas. The device used was too small to produce a commercially profitable well in the chosen medium and the experiment was intended only as a feasibility study (5, 12).

Project Rulison, a joint venture of the Atomic Energy Commission, Austral Oil Company, and the Department of the Interior, was detonated on September 10, 1969. The project can be thought of as a logical successor to Gasbuggy. A higher yield device (40 kt) was used in a more promising gas field, and if gas produced from the stimulated well were meant for sale, the project would be commercially more attractive than Gasbuggy. There have been no announcements of plans for consumer use of gas from the Project Rulison well.

The first phase of Project Rulison consisted of exploding the device to fracture the gas-bearing Mesaverde Formation. The second phase of the experiment will begin about six months after the detonation. This delay will allow decay of most of the radioactive fission and activation products. At this time the cavity will be re-entered by "drill back" operations, and a period of gas analysis and controlled production testing will begin. The primary objective of production testing is to determine the degree of stimulation achieved. Another objective is to determine the fate of the radioactivity remaining from the nuclear detonation, the fraction available for release, and the rate of release. A subsequent phase, not discussed in this report, may involve distribution of the natural gas and consumer use of the gas after possible processing and/or mixing with gas from non-nuclear wells.* The Public Health Service and several other agencies are investigating possible implications to the general population from the use of such gas.

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*Memo: Fred Holzer (LRL) to Distribution, 1/5/70; Subject: "Yield of Gasbuggy Experiment."

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*There is speculation about possible distribution and use of the gas from Rulison (Business Week, August 1, 1970, p. 22). However, criteria have not yet been established for use of natural gas containing radioactivity from nuclear stimulation. Any use or distribution will be possible only with the expressed consent and approval of the AEC. (This footnote was added with the second printing in August 1970.)

II. REPORT OBJECTIVES

This report presents an analysis of the public health implications of radioactivity produced by the Rulison explosion, both that introduced into the hydrologic environment by the explosion and that introduced into the biosphere by flaring gas during production testing. The report includes a brief description of proposed production testing operations and a review of existing plans for an environmental surveillance program for production testing. It is hoped that the report will provide information to assist officials in state and local health departments and other agencies in planning for public safety operations related to production testing.

Much of the information necessary for predicting environmental effects was not available to the public when this report was written, and many of the predictions in this report are based on preliminary data or assumptions.

The radionuclides of primary interest from production testing operations are tritium and krypton-85. Strontium-90 and cesium-137 were also considered in the ground water analysis. Low levels of radionuclides such as carbon-14, argon-37 and argon-39 may also be present in the flared gas, but the quantities produced and their biological significance are such that they are not considered to be of primary concern to public health.

The expectation that concentrations of radionuclides other than tritium and krypton-85 will be small is largely based on experience from Gasbuggy. The reasons for the absence of various radionuclides from the natural gas include (1,30,31):

A. Non-gaseous radionuclides are essentially trapped in the melt at the bottom of the cavity.

B. The six-month delay prior to cavity re-entry allows for decay of the short-lived radionuclides.

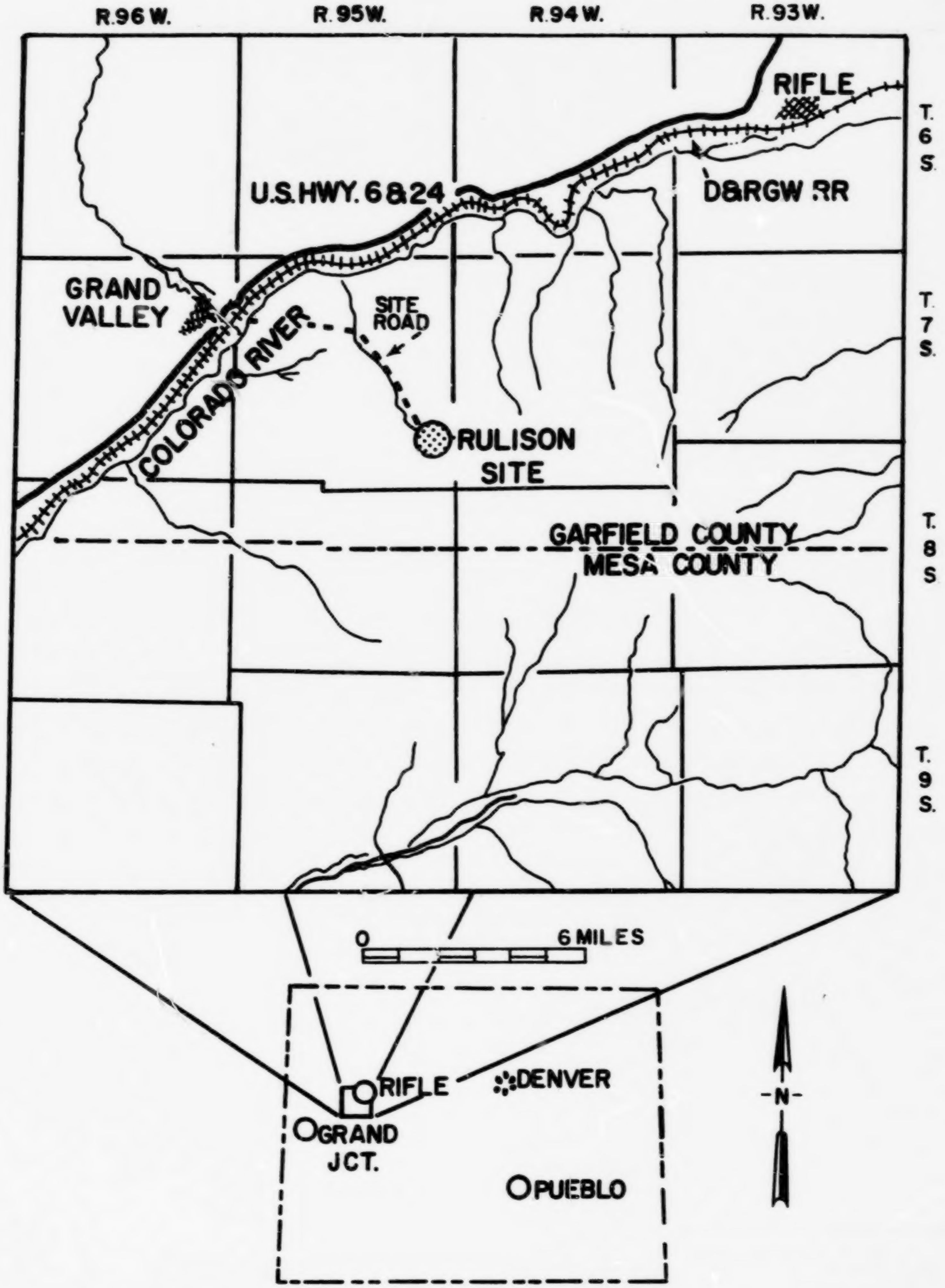
However, Gasbuggy data are based on non-detection in samples that were generally collected for purposes other than quantitating fission and activation products (30). Thus, while there is reasonable certainty that concentrations of fission and activation products such as ^{137}Cs and ^{90}Sr will be very small compared to concentrations of tritium and krypton and will consequently be of little significance to public health, the possibility of their presence should not be ignored. Samples of the chimney gas should be analyzed for fission and activation products and the environmental surveillance program should not assume their absence. Because of the very small chance of the presence of fission and activation products, other than tritium and ^{85}Kr, they will not be given further consideration in this report.

The likelihood of a massive well blow-out during redrilling is very low, but a very small possibility does exist. The consequences of such an event will not be directly evaluated in this report. However, the postulated release during normal production testing operations amounts to 70% of the ^{85}Kr and tritium in the cavity and the AEC has prepared dose estimates for a "maximum hypothetical accident" (38), which is summarized in Appendix H. The environmental surveillance program and the off-site safety program must be predicated on the possibility of such an event.

III. RULISON ENVIRONMENT

Figure 1 indicates the geographical location of the Rulison site. Figure 2 is a map giving the population distribution of the section of western Colorado surrounding and centered on the Rulison site. Morrisania Mesa, the populated area closest to the site, is located about three miles northwest of surface ground zero (SGZ). Grand Valley, a town of about 300 residents, is about six miles to the northwest. Morrisania Mesa is primarily an agricultural community. Agricultural production includes several types of fruit, sheep, beef cattle, and small quantities of milk.

Important terrain features are indicated schematically in Figure 3. Elevations on the figure are given in thousands of feet above mean sea level (1K = 1,000 feet). Movement of air away from Rulison SGZ is primarily controlled by three wind regimes. Valley drainage winds and daily upslope winds in both the Battlement Creek Valley and the Colorado River Valley comprise two separate wind regimes. Regional gradient winds, the third regime, blow generally to the east-northeast above the topographical features throughout the year. The meteorology is described in greater detail in Appendix E.


R.96 W.
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RIFLE
T. 6 S.
U.S.HWY. 6 & 24
D&RGW RR
GRAND VALLEY
SITE ROAD
T. 7 S.
COLORADO RIVER
RULISON SITE
T. 8 S
GARFIELD COUNTY
MESA COUNTY
T. 9 S.
0
6 MILES
RIFLE
DENVER
GRAND JCT.
PUEBLO
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FIGURE 1 INDEX MAP OF PROJECT RULISON SITE (from reference 25)

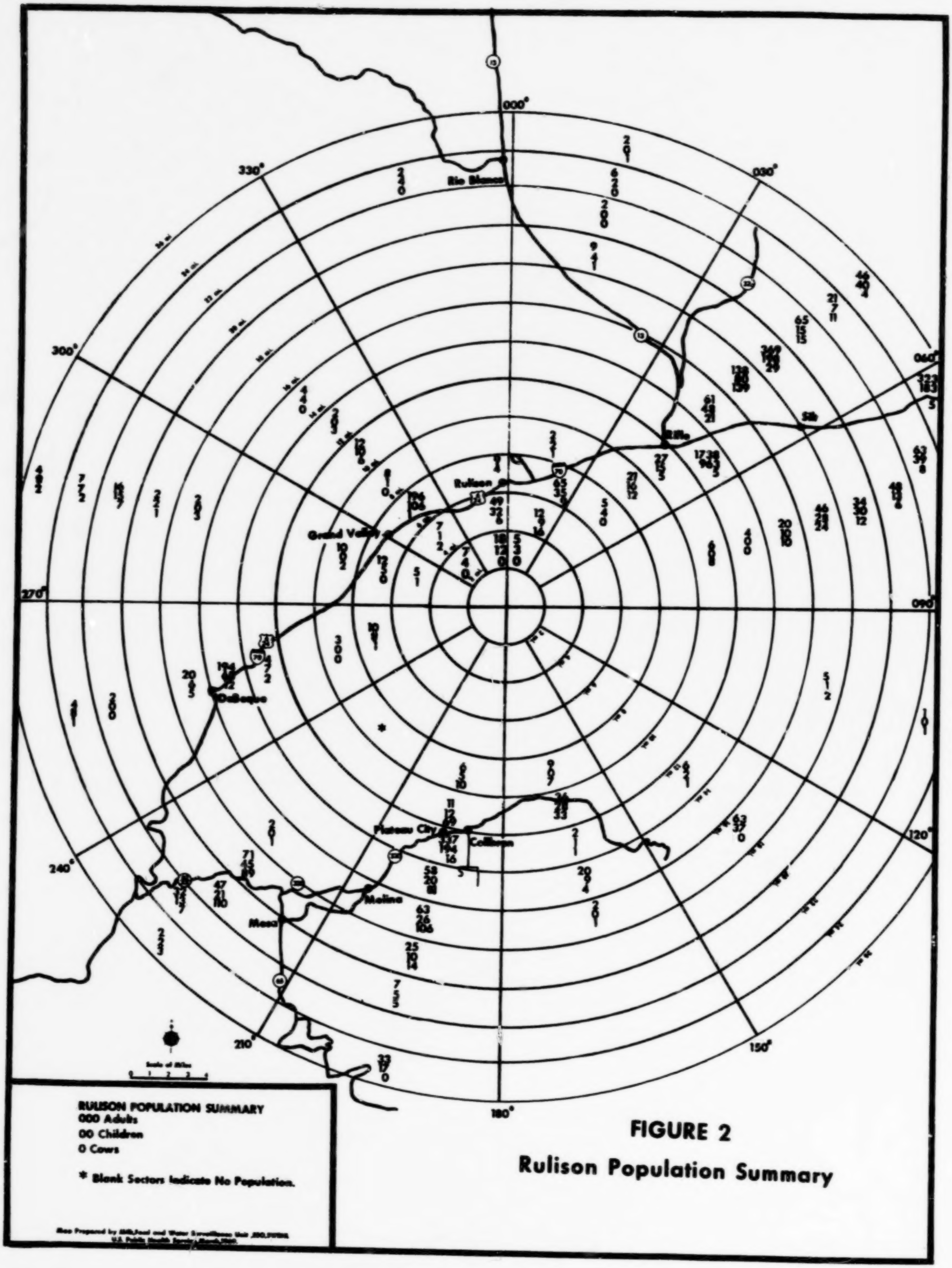
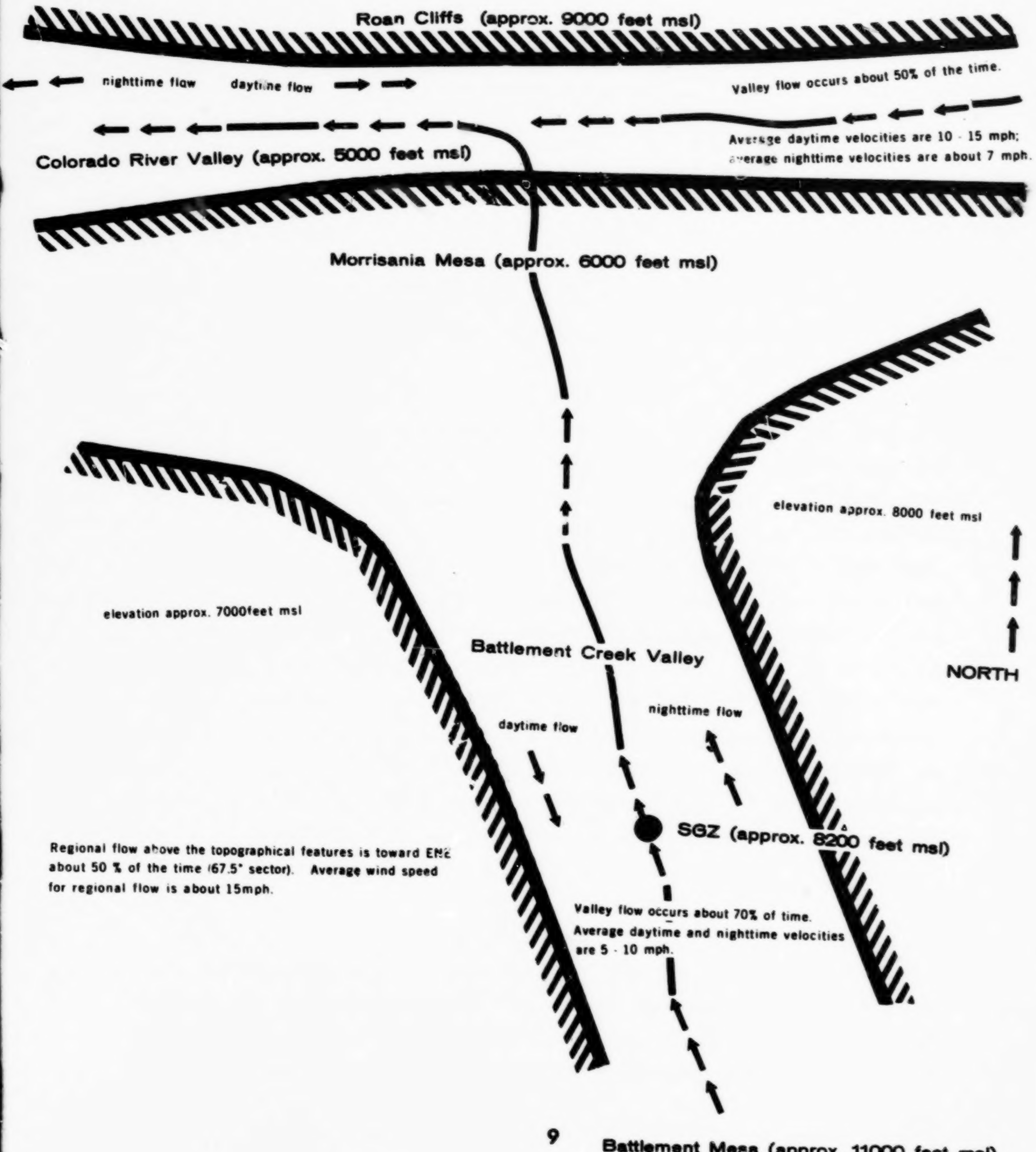

000°
030°
060°
090°
120°
150°
180°
210°
240°
270°
300°
330°
Rio Blanco
Rifle
Silt
Rulison
Grand Valley
DeBeque
Plateau City
Collbran
Molina
Mesa
Scale of Miles
0 1 2 3 4
RULISON POPULATION SUMMARY
000 Adults
00 Children
0 Cows
* Blank Sectors Indicate No Population.

FIGURE 2
Rulison Population Summary

FIGURE 3 Rulison Area Wind Regimes


Roan Cliffs (approx. 9000 feet msl)
nighttime flow
daytime flow
Colorado River Valley (approx. 5000 feet msl)
Morrisania Mesa (approx. 6000 feet msl)
elevation approx. 8000 feet msl
elevation approx. 7000feet msl
NORTH
Battlement Creek Valley
nighttime flow
daytime flow
SGZ (approx. 8200 feet msl)
Battlement Mesa (approx. 11000 feet msl)

Valley flow occurs about 50% of the time.

Average daytime velocities are 10 - 15 mph; average nighttime velocities are about 7 mph.

Regional flow above the topographical features is toward ENE about 50 % of the time (67.5° sector). Average wind speed for regional flow is about 15mph.

Valley flow occurs about 70% of time. Average daytime and nighttime velocities are 5 - 10 mph.

IV. PRODUCTION TESTING

To estimate the ability of the Rulison chimney-fracture system to deliver gas to a pipeline, production tests will be performed. Gas will be released from the wellhead under controlled conditions, and the relationship between the formation pressure, the bottom-hole pressure in the well, and the flowrate of gas will be used to estimate the stabilized deliverability of the well. Production testing has the additional purpose of purging the chimney of radioactivity.

Project Rulison was intended to stimulate gas production by creating a large effective well radius. For nuclear stimulation, the effective well radius is approximately the radius of intense dynamic fracturing. Equation B-1 in Appendix B is a simplified expression for the radial flow of gas into a well under steady-state conditions. Examination of the equation indicates that the gas deliverability should increase as the effective well diameter increases. Pre-shot predictions of geologic effects from Project Rulison indicated that a spherical cavity with a radius of approximately 80 feet would be formed initially, followed by cavity collapse to form a rubble-filled chimney approximately 370 feet high. The rock surrounding the chimney would be fractured to a radius of about 370 feet from the detonation point (20).

Available information on the reservoir characteristics of the Rulison field and the predicted geologic effects of the detonation are used in Appendix B to estimate the stabilized deliverability of the chimney-fracture system from Equation B-1. Use of the equation requires the assumptions that the lateral extent of the paying sandstone lenses penetrated by the chimney-fracture system is large compared to the horizontal extent of intense dynamic fracturing and that these sandstone lenses are of uniform thickness. The assumption must also be made that the reservoir parameters measured in the exploratory hole R-EX (285 feet southeast of the emplacement hole) are characteristic of the paying sandstone lenses for several hundred feet in all horizontal directions from the detonation point. Data reported by the USGS indicate that these assumptions are reasonable (11).

Based on available information and the above assumptions, the stabilized absolute open flow* deliverability of the chimney-fracture system is estimated to be approximately 5.5×10^6 cubic feet per day, NTP**; the maximum possible stabilized open flow deliverability is estimated at 15×10^6 ft^3/day, NTP.

Wells are not commonly tested by open flow measurements, however, and the maximum flaring rate will be different from expected stabilized open flow deliverability. Initial flaring rates can be higher than the stabilized open flow rate predicted by Equation B-1, since the volume of gas contained in the chimney void space is large compared to the flaring rate. Initially at least, flaring gas from the chimney will be analogous to releasing gas from a large tank.

Gasbuggy created a chimney with a void volume of approximately 2.1×10^6 cubic feet. After chimney pressure equilibrated with formation pressure, the volume of gas in place in the chimney was approximately 1.2×10^8 cubic feet

---

*The term "absolute open flow" is defined in Appendix B.

**NTP is an abbreviation for "normal temperature and pressure," 60°F and 14.7 psia.

(corrected to NTP) (12); the initial stabilized open flow deliverability was estimated from production testing to be 2.3×10^6 cubic feet per day (NTP) (4). This was estimated by measuring the rate of decline of bottom-hole pressure while flaring at 5×10^6 ft^3/day (NTP), measuring the subsequent increase in bottom-hole pressure while flaring at 0.75×10^6 ft^3/day, and using a straight-line interpolation between the two observations to predict the flow-rate at which bottom-hole pressure would remain constant. A back-pressure curve was then used to calculate the equivalent open-flow rate (4).

Plans for production testing of Rulison have not yet been announced, but the assumption that Rulison testing will follow the pattern adopted for Gasbuggy seems reasonable.* This would indicate an initial flaring rate of twice the open flow deliverability, or an expected rate of approximately 11×10^6 ft^3/day with a possible maximum rate of 30×10^6 ft^3/day.

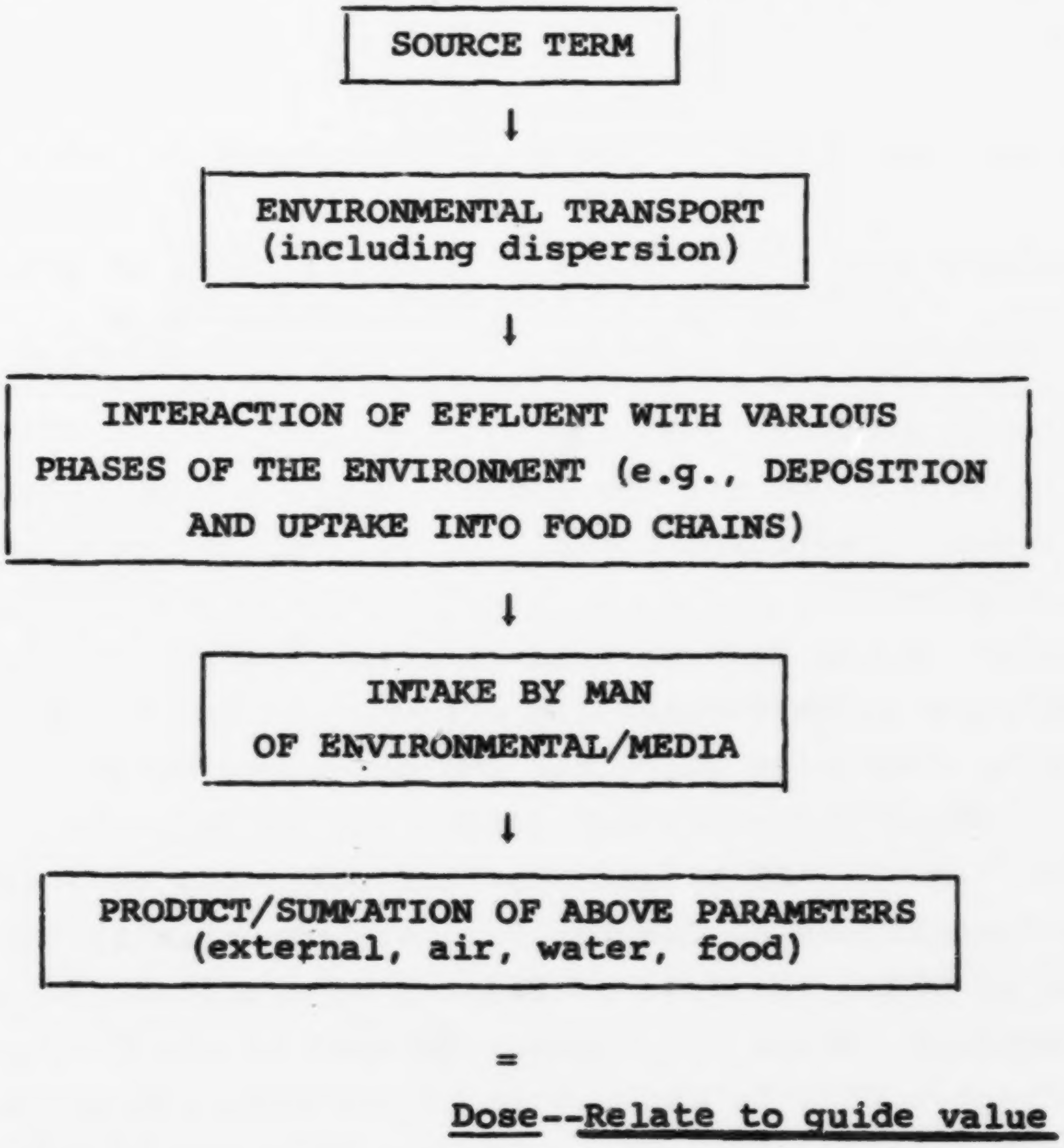
Tables of the quantities of radionuclides produced by the Rulison explosion and calculations for predicting the resulting concentrations of tritium and ^{85}Kr in the natural gas are given in Appendix C. The concentrations are based on the assumption that radioactivity produced by the explosion will be diluted in the gas contained in the chimney. The ^{85}Kr concentration in natural gas is estimated to be about 1.4×10^{-4} μCi/cm^3 when production testing is initiated. The tritium concentration in natural gas at the initiation of production testing is expected to range from 0.7×10^{-4} μCi/cm^3 to 15×10^{-4} μCi/cm^3 based on the calculations of Appendix C.

---

*Plans for production testing have been announced (reference 38, see Appendix H), but do not affect the conclusions of this section.

V. ENVIRONMENTAL RADIOACTIVITY

To evaluate the implications to man of releasing radioactivity to the environment, the resulting contamination to the total environment must be examined and the subsequent transport of the pollutants to man and associated radiation dose to man must be estimated. The general approach used in analysis of environmental releases and their impact on man corresponds to the diagram below:


SOURCE TERM
ENVIRONMENTAL TRANSPORT (including dispersion)
INTERACTION OF EFFLUENT WITH VARIOUS PHASES OF THE ENVIRONMENT (e.g., DEPOSITION AND UPTAKE INTO FOOD CHAINS)
INTAKE BY MAN OF ENVIRONMENTAL/MEDIA
PRODUCT/SUMMATION OF ABOVE PARAMETERS (external, air, water, food)
=
Dose--Relate to guide value

To assess the health implications, the estimated dose must be compared with a public health guide (e.g., radiation protection guides).* The evaluation must include a summation of the various related doses (e.g., all doses to a particular organ). For instance, possible pathways for tritium include:

1. inhalation and uptake through the skin from air,
2. ingestion of contaminated food products (vegetation, milk, etc.), and
3. ingestion of water.

Doses from all pathways must be summed to determine the dose to the organ of interest.

Radioactivity in the environment is considered in two sections:

1. Concentrations and movement of radionuclides in ground water.
2. Environmental concentrations resulting from surface releases.

---

*The philosophy of the PHS group for the evaluation of Plowshare projects is to use the radiation protection guidelines of the Federal Radiation Council (37). The FRC recommendations are generally given in terms of dose guides for particular organs rather than as concentration guides for specific radionuclides in particular compartments of the environment (milk is an exception where the FRC has given concentration guides). Where concentration guides are needed, the standards in AEC Manual, Chapter 0524, are referenced. The recommendations of Chapter 0524 are essentially the same as those of Title 10, Code of Federal Regulations, Part 20. Both generally follow the recommendations of the FRC. AEC Manual Chapter 0524 is applicable to projects conducted under contracts or agreements with the AEC, and 10 CFR 20 applies to operations conducted under a license arrangement.

RADIOACTIVITY IN GROUND WATER

Isotopes, Inc., an AEC safety contractor, predicted concentrations and movement of radionuclides in water for the Rulison detonation and concluded that the occurrence of levels of radioactivity exceeding the applicable concentrations guides was not likely at any use point (15). The nearest use point for ground water is the rural community of Morrisania Mesa, approximately three miles from the detonation point, where the major sources of water for domestic use are shallow wells penetrating alluvium (11). Morrisania Mesa lies approximately 6,000 feet above the detonation point, and almost the entire thicknesses of the Mesaverde and Wasatch Formations separate the water-bearing alluvium from the Rulison chimney. Movement of radionuclides from the chimney to the alluvium is very improbable. Movement of radionuclides to the Colorado River, which lies about 5,000 feet above the chimney and at least five miles distant, is also unlikely.

While gas is being released from the well, hydraulic gradients in the formation surrounding the chimney will drive water toward the chimney because chimney pressure will be lower than the pore pressure of the formation. Until gas production from the well ceases, no migration of radioactivity away from the chimney is expected.

The analysis given in Appendix D indicates that the transport of radioactivity by ground water from the Rulison chimney to any ground water use point is extremely unlikely.

BIOSPHERE CONCENTRATIONS

The scope of this section is limited to consideration of tritium and ^{85}Kr. Other radionuclides which may be released include ^{14}C, ^{37}A, and ^{39}A. However, because of the combination of the small concentrations of these nuclides expected to be present in the gas and their relative biological significance compared to tritium and ^{85}Kr, these three nuclides will not be considered.

The transport of airborne effluent from the Rulison site is affected by three wind regimes; the Battlement Creek drainage and upslope winds and the upper level or regional gradient winds. The Battlement Creek nighttime drainage winds flow into the Colorado River Valley drainage wind regime. The effective stack height or plume rise will determine what fraction of the effluent is transported in each of these regimes. Based on the information in Section III and Appendix E, it is assumed that the majority of the effluent will rise above the local terrain to be transported by the regional gradient winds. Prevailing direction of the gradient winds is toward the ENE. It is logical to assume that a fraction of the effluent will also be entrained in the Battlement Creek Valley flow (see Appendix E). This would result in the shortest possible transport distance (about three miles) to a populated location.

The many assumptions which must be made in estimating the doses to humans which might result from Rulison production testing make difficult any truly accurate estimates. Estimates developed in the following section should be regarded as rough dosage approximations. The discussion outlines the possible pathways for doses to humans from radioactivity released during production testing. The object is to estimate doses which might be expected to occur rather than maximum credible doses.

TRITIUM

Downwind surface concentrations of tritium can be estimated by assuming a flaring rate of 2×10^7 ft^3/day (NTP) and a tritium concentration in the chimney gas of about 42 $\mu Ci/ft^3$ (1.5×10^{-3} $\mu Ci/cm^3$; see Appendix C), equivalent to an activity release term of about 9.7×10^3 µCi/sec. Assuming a constant dispersion coefficient for the range from two to ten miles downwind, as discussed in Appendix E, the expected average tritium concentration in this distance range would then be on the order of 3×10^{-11} $\mu Ci/cm^3$ of air (short term concentrations may be up to several orders of magnitude above this).* The figure of $3 \text{x} 10^{-11}$ $\mu Ci/cm^3$ is several thousand times less than the concentration guide of 7×10^{-8} $\mu Ci/cm^3$ recommended by AEC MC-0524 (39) for a suitable sample of the population (individual guides divided by 3 as suggested by FRC).

The figure of 3×10^{-11} $\mu Ci/cm^3$ is the estimated average concentration over a period of days to weeks and is based on an assumed continuous release at the maximum expected flaring rate and tritium concentration. The initial tritium concentration in the gas could well be as little as five percent of the average value assumed and will decrease with the volume of gas flared.

An adult breathing air containing a tritium concentration of 3×10^{-11} $\mu Ci/cm^3$ for 24 hours a day for 10 days would receive an inhalation dose of 6×10^{-7} rem for an adult.**

---

*The nearest population to the site is three miles. The dispersion coefficient of 3×10^{-9} sec/m^3 is based on crosswind averaging in the predominant wind sector.

**The present proposals involve flaring three days and then shutting in the well for about a week. Three high volume flaring periods are contemplated (9 days of flaring over approximately a three-week period; considered to be 10 days of flaring to include initial tests).

This is 3×10^5 times less than the FRC guide of 0.17 rem per year. If it is assumed that a person receives an equivalent dose from tritium uptake through the skin (29,32) then the dose would be about 1.2×10^{-6} rem. The inhalation dose for an infant is about half of that for an adult and the combined inhalation plus skin dose is about 40% of that for an adult.* It is unlikely that the exposure from inhalation will approach a significant fraction of the guides.

The calculation for dose per µCi intake of tritium is indicated in Appendix F.

The following discussion develops an estimate of potential tritium uptake through food and water:

> Following the November 1968 production testing of Gasbuggy, the tritium concentration in vegetation ranged

---

$$* \quad \frac{\text{Infant breathing rate } 5\ \text{m}^3/\text{day (41)}}{\text{Adult breathing rate } 20\ \text{m}^3/\text{day (33)}} \times \frac{3.1\ \text{day } t_{\text{eff,}}\ \text{infant}}{10\ \text{day } t_{\text{eff,}}\ \text{adult}} \times$$

$$\frac{\text{Adult body weight 70 kg (33)}}{\text{Infant body weight 10 kg (40)}} = 0.5$$

To estimate the relative uptake through the skin, assume the relative uptake is proportional to the skin area and that the skin area can be related to the body mass to the 2/3 power (mass is a function of length cubed, whereas, area is a function of length squared). Therefore, the tritium uptake through the skin of an infant is $(10/70)^{2/3} = 0.27$ times that of an adult.

up to 36 pCi/ml of moisture.* Based on the proposed flaring parameters for Rulison, it is estimated that tritium concentrations in vegetation moisture in the Rulison area may range up to an order of magnitude higher. Assuming that a person daily consumes 220 grams of vegetation grown at the point of maximum concentration and that the average vegetation moisture content is 0.9 ml/g, a person would ingest about 0.07 µCi of tritium per day. Ingestion at this level corresponds to a dose for an adult of about 7×10^{-6} rem for each day of ingestion.

Concentrations of tritium in milk would be roughly an order of magnitude less than concentrations in vegetation moisture because of dilution by the cows' drinking water.** Thus, a person drinking one liter of milk per day would ingest about 0.04 µCi of tritium per day.

The estimated long-term average airborne tritium concentration is 3×10^{-11} $\mu Ci/cm^3$, whereas, the short-term air concentrations (minutes to hours) may be several orders of magnitude higher.* The long-term average concentration corresponds to a specific activity of tritium in condensed atmospheric moisture of about 10 pCi/ml.** The short-term average air concentration corresponds to a concentration of 10^4 pCi/ml in moisture. Thus, the previously estimated concentration of 360 pCi/ml of plant moisture does not appear unreasonable.

---

*In June and July of 1968, approximately 6×10^7 ft^3 (NTP) of gas with a tritium concentration between 10-17 $\mu Ci/ft^3$ (concentration decreased with time) was flared. The wellhead was then shut in until November, when flaring began at a flowrate of 3.5×10^6 ft^3/day, with a concentration of 10 $\mu Ci/ft^3$ (28). One vegetation sample contained 36 pCi/ml of tritium in moisture; concentrations in all other samples were less than half of this value.

**This assumes a cow receives only 0.1 of its water from vegetation.

It is difficult to conceive of a reasonable mechanism whereby large volumes of water used for human consumption could become contaminated to levels equal to the specific activity of the tritium in atmospheric moisture. If the water contained 1/10 of the average specific activity, a person drinking 2,200 ml/day would ingest about 0.002 μCi per day of tritium.+

The estimated tritium intake through inhalation and skin absorption is about 0.001 μCi per day assuming an average tritium concentration in air of 3×10^{-11} μCi/cm^3.

---

*Using Pasquill D conditions, 7 mph wind speed, and a ground level release, the short term concentration at 3 miles (over a period of minutes) at the nearest downwind populated location would be about 10^{-8} μCi/cm^3.

**Assuming temperature of 50° F, relative humidity of 40%, and barometric pressure of 750 mb, and that all tritium is present as HTO.

+Battlement Creek is used to periodically fill cisterns used for potable water. The SWRHL surveillance program (Section VI) includes appropriate sampling. Should the creek become contaminated by rain scavenging, appropriate action can be taken.

The total tritium intake (for an adult) from the previously mentioned pathways is:

	nCi/day*
Inhalation and skin	1
Vegetation	70
Milk	40
Water**	2

This is equivalent to a dose of about 10^{-5} rem per day of exposure for an adult and about the same or slightly less for an infant.[+]

KRYPTON-85

Assuming a flaring flowrate of 2×10^7 ft^3/day (NTP) and a krypton-85 concentration in the chimney gas of 4 $\mu Ci/ft^3$; ($1 \times 10^{-4} \mu Ci/cm^3$; see Appendix C), the equivalent source term is $9.2 \times 10^2 \mu Ci/sec$. Using the dispersion coefficient of 3×10^{-9} $\mu Ci/m^3 : \mu Ci/sec$ for the range from one to ten miles downwind the long-term average krypton-85 concentration in this range would be 2.8×10^{-12} $\mu Ci/cm^3$ of air. This concentration is a factor of 4×10^4 below the AEC MC-0524 concentration guide of 10^{-7} $\mu Ci/cm^3$ for a suitable sample of the population in an uncontrolled area. This is equivalent to a dose of about 4×10^{-5} mrem per day of exposure (see Appendix G for assumptions), or 4×10^{-4} mrem for over a period of ten days.*

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*These estimates are predicated on the maximum possible gaseous concentrations. Actual gaseous tritium concentrations are expected to be as much as an order of magnitude lower.

**ICRP (33) indicates 2.2 l/day consumption for standard man. If it is assumed that a man consumes 1 liter of milk per day, this off-sets the water consumption and reduces the tritium intake via water to 1 μCi/day. The water in vegetation also off-sets liquid consumption.

[+] An infant consumes less vegetation and water than an adult, but this is off-set by the infant's smaller body mass.

The assumed concentrations and flowrates on which the above calculations are predicated would result in the release of about 70 per cent of the total source term for tritium and ^{85}Kr during the initial high flowrate tests over a ten-day period. Production testing operations will include not only the initial high flowrate tests but also intermediate and low flowrate tests which will last for months. Radioactivity released during the high flowrate tests will probably be less than the amounts assumed above, but radioactivity will also be released during the subsequent tests. Doses estimated above should be representative of the potential radiation doses from radioactivity releases during the total flaring operation.

---

*The assumption of an infinite spherical cloud instead of a semi-infinite spherical cloud in the ^{85}Kr dose estimate is intended to compensate for any dose resulting from retention of ^{85}Kr in body fat (see Appendix G). The calculation is for the surface dose rather than the dose at some depth within the body. The depth dose at 7 mg/cm^2, the approximate thickness of the outer epidermal layer, is about one-half of the surface dose (34). The gamma dose contribution for Kr-85 is about one-hundredth of the surface beta dose.

TOTAL DOSE--ACUTE PLUS CHRONIC

The previous sections on tritium and ^{85}Kr dose have indicated maximum exposures during the high flow-rate production testing period (acute exposure). Subsequent to the high flow-rate tests there will be low-level releases associated with additional tests (the dose from these additional tests has been considered by the assumptions used for the high flow-rate tests). But, of possibly more importance will be the chronic exposure from the residual radioactive effluent from the high flow-rate tests remaining in the environment. The estimated ^{85}Kr dose is several orders of magnitude less than that for tritium and ^{85}Kr is basically inert and thus dispersed in the atmosphere; whereas, tritiated moisture is retained in plants and soil with a fairly long effective half-life (tens of days; see Appendix I). Therefore, this section will deal only with the chronic dose from tritium.

The model used to assess the potential dose from both the acute and chronic tritium exposure is presented in Appendix I. The model considers two phases of environmental concentration:

1. Assume that the environmental vegetation moisture concentration reaches 360 pCi/ml instantaneously with the initiation of high flow-rate production testing and is maintained at this concentration for three weeks (three 3-day production tests over a 3-week period). Among other things, this assumes that 70% of the upper source term estimate for tritium is released during this period. The actual quantity of tritium produced may be lower by an order of magnitude, and it is likely that only 10% of that

produced will be released*.

This approach is used to arrive at conservative estimates of initial tritium concentrations in the environment and also to account for the dose that may be accrued from subsequent releases during lower flow-rate testing**.

2. At the end of the 3-week production test phase, the vegetation moisture concentration of 360 pCi/ml of tritium was allowed to decay with an effective half-life of 85 days (see Appendix I for discussion of the half-life).

The dose to man is then calculated based on the build-up and eventual decay of the tritium concentration in body water as a function of the tritium concentration in man's intake and the biological effective half-life.

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*This expected conservatism of two orders of magnitude is relevant not only here, but is also implicit in the previous tritium dose estimates.

**A low release fraction during initial production testing results in a greater potential source term for subsequent tests.

Table 1 summarizes the estimated doses from Project Rulison. The results are reported for three time periods; (1) dose as a result of one day's exposure at the peak production testing flow-rate, (2) dose from exposure during the total peak production testing period (three weeks, including three 3-day testing periods) and the dose from the total operation.

TABLE 1
RULISON DOSE ESTIMATES

Radionuclide	Average Daily Dose Peak Flaring Rate mrem	Acute Period First 3 Weeks mrem	Chronic Period (Residual) mrem
^{85}Kr			
External*	4×10^{-5}	4×10^{-4}	
Tritium			
Inhalation	6×10^{-3}	6×10^{-2}	
Ingestion	10^{-2}	0.2	3

TOTAL DOSE FROM OPERATION - 3 mrem

The important conclusions to be drawn from this information are:

1. The chronic dose from tritium in the environment may be roughly an order of magnitude greater than the dose during the actual flaring operation.

2. The potential tritium dose is greater than the potential ^{85}Kr dose; and ingestion is the most significant uptake pathway for tritium.

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*Largely beta skin dose.

3. The conservative total dose estimate for the Rulison production testing is 3 mrem; considering the previously mentioned conservative assumptions (tritium production and release fraction), the actual dose will probably be in the range of 0.1 mrem or less.

The population information (in Figure 2, page 8) indicates there are at most several hundred people within the area covered by this dose estimate. All of these people will not be in the area of the highest concentrations and few, if any, of them will be consuming foodstuffs containing tritium at the concentrations postulated in this section.

VI. ENVIRONMENTAL SURVEILLANCE

Average airborne concentrations of tritium are expected to be three orders of magnitude below the concentration guide at off-site populated locations, and average airborne concentrations of ^{85}Kr are expected to be four orders of magnitude less than the concentration guide. Tritium concentrations in vegetation moisture can be expected to be a few picocuries per milliliter to a few hundred pCi/ml. Tritium concentrations in milk should be an order of magnitude less than the concentration in vegetation moisture. No significant environmental concentrations of any other radionuclides are expected. Migration of radioactivity away from the chimney through ground water is considered unlikely. If such migration does occur, velocities of movement will be small. Occurrence of significant concentrations of radioactivity at any ground water use point is highly improbable.

Although radionuclide intake by residents in the Rulison area is not expected to approach the levels of the applicable public health guides, environmental surveillance must be performed to verify actual environmental concentrations of important radionuclides since the estimates of environmental concentrations are based on assumptions. Radiation doses to the area residents can then be estimated more accurately from measured levels.

An adequate environmental surveillance program should also obtain information useful in health evaluations of similar projects in the future. Determinations of actual plume rise, points of maximum concentration at surface level, and tritium concentrations in vegetation moisture and milk should be made, both for health considerations and to aid in predicting environmental concentrations of tritium which may result from future gas stimulation projects.

The surveillance program proposed by the Southwestern Radiological Health Laboratory has been reviewed. This plan, prepared under a Memorandum of Understanding with the AEC, was presented in the "Off-Site Radiological Surveillance Plan--Project Rulison Drill-Back and Flaring Program," October 1969, and was supplemented by the program outlined in NVO-61.* The program includes analysis for tritium, fission products, and activation products in: (1) air samples; (2) samples of foods and drinking water used by wildlife, domestic animals, and humans; and (3) precipitation samples. The program includes collection and analysis of background samples.

Although tritium and ^{85}Kr are the only radionuclides expected to be released in detectable quantities, a significant part of the total environmental surveillance effort is oriented towards other fission product radionuclides (radioiodines, strontium, ^{137}Cs, etc.). It is prudent to establish a program to document the levels of these fission products, even though their release is not expected. However, most of the effort should be devoted to sampling for radionuclides which are expected in the flared gas.

The rural community of Morrisania Mesa is located 3 miles down-wind in the path of Battlement Creek Valley drainage winds. There are fruit orchards (apples, peaches, and a few plum and apricot trees), and milk cows in the area. Since radiation doses from ingestion of tritium may be equal to or greater than doses from inhalation, attention should be given to food products grown in this area.

The proposed SWRHL program appears to be adequate not only to determine environmental levels of concern to public health, but also to document the environmental concentrations of radionuclides caused by Rulison production testing. Sensitivities for detection are several orders of magnitude below the FRC and AEC guides.

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*Draft, November 1969.

The surveillance program for Rulison production testing should be designed to obtain information concerning the following:

1. Effluent plume rise; not so much because of its effect on atmospheric diffusion, but rather because it determines the transport direction and thus the population at risk due to the various wind regimes at the Rulison site.

2. Maximum concentrations, and changes with time, of tritium in the water associated with various types of vegetation (milk cow forage, domestic animal forage, and vegetation for human consumption--assuming the concentrations will vary in the different vegetation species), milk and potable water.

3. The effective half-life of tritium in vegetation in the Rulison environment. The proper determination of the half-life will require a minimum sampling time interval of one or more samples per half-life period.

4. If possible, bioassay samples (urine), should be obtained to give an indication of actual doses.

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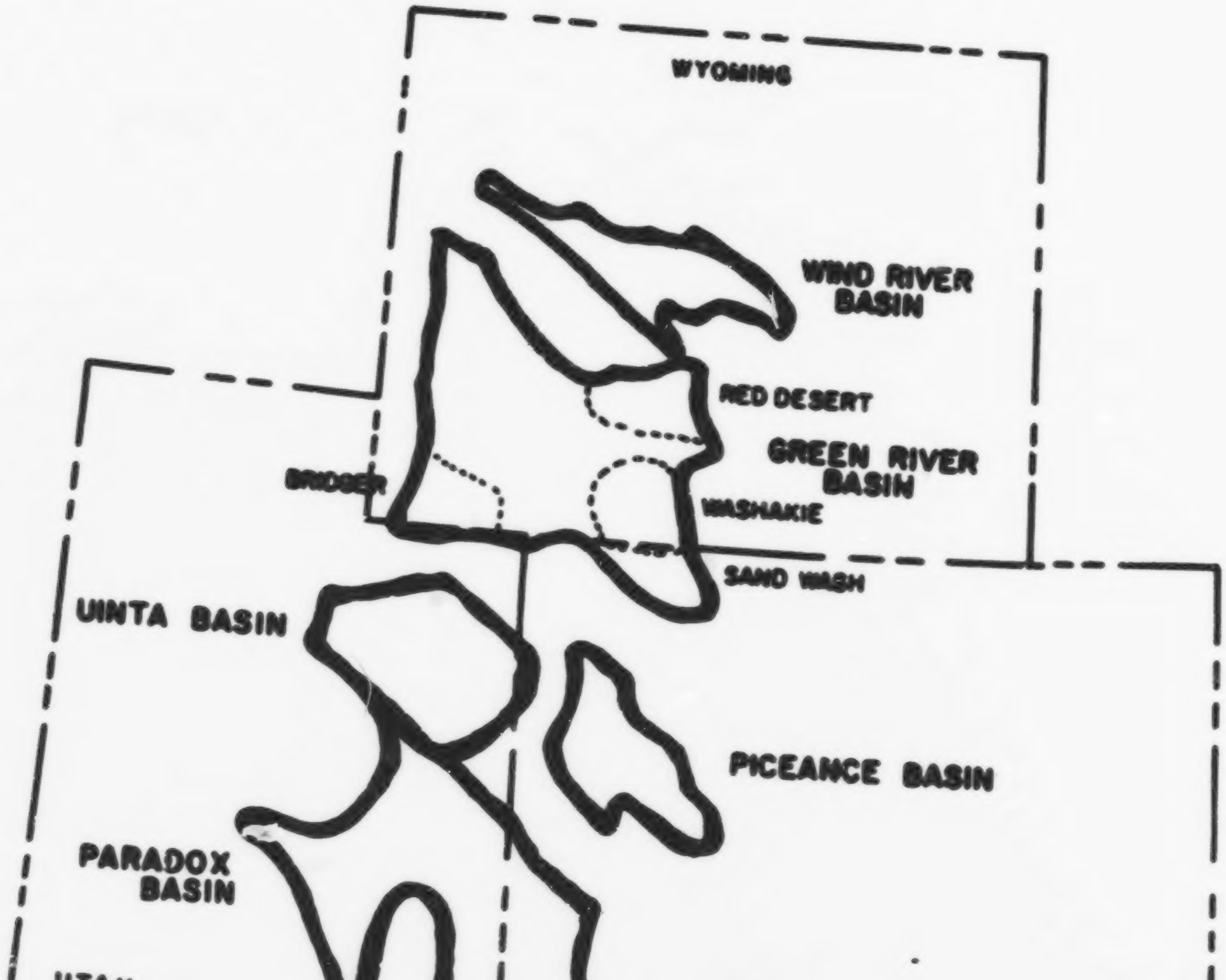
A-1

MAJOR BASINS OF THE ROCKY MOUNTAIN STATES


WYOMING
WIND RIVER BASIN
RED DESERT
GREEN RIVER BASIN
BRIDGER
WASHAKIE
SAND WASH
UINTA BASIN
PICEANCE BASIN
PARADOX BASIN
UTAH
ARIZONA
COLORADO
NEW MEXICO
SAN JUAN BASIN

APPENDIX A

THESE BASINS CONTAIN SUFFICIENT RESERVOIR THICKNESSES TO MERIT CONSIDERATION FOR N E STIMULATION.

(from reference 35)

APPENDIX B

GAS DELIVERABILITY

An expression for gas deliverability from a well can be derived by assuming that the paying strata penetrated by the well are of uniform thickness and infinite extent and are isotropic and homogeneous, and that flow is compressible and Darcian. With these assumptions, the radial flow of gas into a well under steady-state conditions at a given point in time is given by (19, 20):

$$Q = \frac{10.320\ kh(P_e^2 - P_w^2)}{u \ln (r_e/r_w)\ T_f\ (14.65)\ z} \qquad \text{(Equation B-1)}$$

WHERE:

Q = Rate of flow in cubic feet per day at a pressure base of 60°F and 14.65 psia (NTP).

k = Permeability of the paying strata, in millidarcys.

h = Net thickness of the paying sandstone between two confining layers, in feet.

P_e = Formation pressure in psig at the effective radius of drainage, r_e.

P_w = Flowing pressure at the face of the wellbore, in psia, r_w is the effective radius of the wellbore. Absolute open flow deliverability (AOF) is calculated by setting P_w = 1 atm.

u = Viscosity in centipoise, of the gas, approximately 0.015.

T_f = Formation temperature, degrees Rankine.

z = Gas deviation factor.

Sufficient information has been published to permit use of Equation B-1 to predict the initial deliverability of the Project Rulison chimney-fracture system. For the overall Rulison field, average reservoir properties are given as (10, 11, 21):

k = 0.5 millidarcys (sandstone lenses)

P_e = 2700 psia

z = 0.88

On the average, the Mesaverde Formation in the Rulison field contains a net thickness of 500 feet of paying sandstones out of a total formation thickness of approximately 2500 feet (21). Assuming the paying sandstone lenses are uniformly spaced throughout the thickness of the Mesaverde, a chimney 370 feet high would intersect approximately 74 feet of paying sandstones. The sandstones are not likely to be uniformly spaced, and good design would locate the chimney to intersect as much sandstone as possible, but no other assumption is possible without more detailed geologic information.

Average reservoir properties observed in the exploratory hole R-EX are given as (10):

k = 0.11 millidarcys (sandstone lenses)

T_f = 215°F = 675° Rankine (at 8400 feet subsurface)

A net thickness of 375 feet of paying sandstone out of a total formation thickness of 1162 feet was observed in R-EX; a chimney 370 feet high would penetrate approximately 120 feet of paying strata, assuming uniform spacing of the sandstone lenses.

Nuclear stimulation is thought to increase the effective well radius to the radius of intense dynamic fracturing, estimated to be approximately 370 feet for Project Rulison. The above data can be used with Equation B-1 to estimate the "absolute open flow deliverability" (AOF) of the chimney-fracture system. The absolute open flow deliverability is that flow which would occur if pressure at the well face (i.e., in the chimney) were reduced to one atmosphere. Using the reservoir parameters reported for R-EX and an assumed drainage area of 160 acres, the "expected" initial AOF deliverability is estimated to be 5.5 x 10^6 ft^3/day; an expected "maximum" initial AOF deliverability can be estimated from the average parameter values for the Rulison field as 15.3 x 10^6 ft^3/day, assuming that the permeability of a large area is not likely to exceed the average permeability of the paying sandstones.

The use of Equation B-1 to predict AOF deliverability implicitly assumes that the sandstone lenses have large horizontal dimensions compared to the radius of fracturing, are of uniform thickness, and are homogeneous. Data reported by the USGS (11) indicate that the lenses may be several thousand feet long; if so, the initial deliverability may be reasonably approximated by Equation B-1.

Equation B-1 represents a very simple approach to reservoir engineering. Techniques actually used by petroleum companies to predict deliverability are more sophisticated. Such techniques generally involve finite-difference computer solutions of time-dependent partial differential equations which take into account variation of fracturing with distance from the detonation point. Effective use of these techniques requires better knowledge of the geology of the field than is presently available to the public. Detailed descriptions of reservoir characteristics are included in the "Project Rulison Feasibility Study" but the information has not been released by Austral Oil. Estimates of deliverability are included in the "Pre-Shot Reservoir Evaluation" by Austral Oil/CER which presently (as of November 1969) exists only in draft form and is not available to the public (22).

Since the gas flow rates which will occur during production testing will be as much the result of administrative decisions as of engineering calculations, it is felt that use of Equation B-1 will yield acceptable estimates.

APPENDIX C
RADIOACTIVITY IN GAS

Table C-1 gives estimated quantities of selected radionuclides produced by the Rulison device. The radionuclides of chief interest in consideration of gas use are Krypton-85 and tritium, since these two isotopes will be found in gas released from the chimney. Estimation of the concentrations of these isotopes in the gas requires knowledge of the amount of the isotopes produced by the device, the void volume of the chimney, the pressure in the chimney at the time flaring begins, the bottom-hole temperature, and the water content of the formation.

The calculation for Krypton-85 is straightforward. From Table C-1, approximately 960 curies of ^{85}Kr were produced by the detonation. The void volume of the chimney is approximately equal to that of a sphere with a radius of 80 feet, about 2.1×10^6 cubic feet.

The bottom-hole temperature of the chimney at the time of re-entry is estimated to be about 380°F, based on experience with Gasbuggy.* The bottom-hole pressure at the time of

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*The Gasbuggy detonation raised temperatures in the chimney from the pre-shot formation temperature (130°F) to 247°F (4). Cavity dimensions and materials for Rulison are similar to those of Gasbuggy, so the temperature increase should be proportional to the ratio of energy yields of the respective devices (29 KT for Gasbuggy--LRL Memo, 5 January 1970). 215°F + (40 KT/29 KT) (117°F) = 376°F or 380° F. There are obvious uncertainties in this estimate.

TABLE C-1

RADIONUCLIDE ACTIVITY AT T_o + 180 DAYS RESULTING FROM DETONATION OF 40 FISSION KILOTONS

Nuclide	Half-Life	Curies
^{85}Kr	10.76 y	0.96×10^3
^{89}Sr	50.6 d	0.91×10^5
^{90}Sr	28.8 y	0.59×10^4
^{91}Y	59 d	1.01×10^5
^{95}Zr	65 d	1.82×10^5
^{95}Nb	35 d	0.32×10^8
^{103}Ru	40 d	0.41×10^5
^{103}Rh	57 min	0.41×10^5
^{106}Ru	1.0 y	1.52×10^5
^{106}Rh	30 sec	1.52×10^5
^{131}I	8.05 d	1.13
^{133}Xe	5.27 d	0.86×10^{-3}
^{137}Cs	30 y	0.75×10^4
^{137}Ba	2.6 min	0.69×10^4
^{140}Ba	12.8 d	0.34×10^3
^{140}La	40 h	0.40×10^3
^{141}Ce	32.5 d	0.52×10^5
^{143}Pr	13.7 d	0.63×10^3
^{144}Ce	285 d	1.47×10^5
^{144}Pr	17.3 min	1.47×10^5
^{147}Pm	2.6 y	0.28×10^5
^{3}H	12.27 y	1.0×10^4

From reference 15.

re-entry is estimated to be about 2640 psia.* The volume of gas in the chimney is estimated to be about 2.4×10^8 cubic feet (NTP), and the corresponding ^{85}Kr concentration is estimated to be about 4.0 $\mu Ci/ft^3$ (1.4×10^{-4} $\mu Ci/cm^3$). This figure is less than a factor of two higher than the AEC predicted ^{85}Kr concentration of 0.8×10^{-4} $\mu Ci/cm^3$ (28).

Estimation of tritium concentrations is more difficult. The most conservative approach assumes that all of the tritium will exchange with hydrogen attached to gaseous hydrocarbons. In this case, the tritium concentration in the gas flared from the well-head would be 10 kCi/2.4×10^8 cubic feet = 42 $\mu Ci/ft^3$ (1.5×10^{-3} $\mu Ci/cm^3$). This approach is excessively conservative, since it implies that there is no exchange of tritium with water-bound hydrogen. In Gasbuggy, approximately 95% of the tritium produced by the nuclear device appears to have eventually exchanged with water-bound hydrogen in the chimney to appear as HTO (12). A pre-shot estimate of tritium in Gasbuggy gas using the same conservative assumption would have predicted a concentration of about 320 $\mu Ci/ft^3$, but the highest concentration measured, 100 $\mu Ci/ft^3$, was observed in a sample taken the day after the detonation (12). The tritium concentration in the gas decreased to approximately 18 $\mu Ci/ft^3$ within 36 days after the detonation (12).

Assuming a similar reduction of the tritium concentration in Rulison gas would lead to a predicted value of about 2 $\mu Ci/ft^3$

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*Re-entry well-head pressures are estimated at 2400 psia by the AEC (Press Release NV-69-135). Assuming uniform gas temperatures of 380°F and gas of pure methane, the bottom-hole pressure would be about 2640 psia. Actual pressures will be somewhat higher, since the gas will contain other species of higher molecular weight.

when flaring begins at least six months after the detonation. However, this assumption is probably not reasonable either, since water may have flowed into the Gasbuggy chimney from the Ojo Alamo Formation (13), while it is unlikely that large quantities of water will enter the Rulison chimney. Some reduction will undoubtedly occur, since the Mesaverde sandstones near the chimney contain about 4% water by volume (11), but there appear to be no overlying aquifers near the chimney. The actual tritium concentration should be somewhere between 2 $\mu Ci/ft^3$ and 40 $\mu Ci/ft^3$. An "expected" value can be computed by assuming that the initial reduction of tritium concentrations in Gasbuggy gas (from 320 $\mu Ci/ft^3$ to 100 $\mu Ci/ft^3$) was caused by tritium exchange with water in the immediate vicinity of the chimney, and that water from the Ojo Alamo did not enter the chimney until several days after the detonation. Both the Gasbuggy and Rulison media have approximately the same water content, so a similar reduction might be expected for Rulison; this assumption would result in a predicted tritium concentration of about 13 $\mu Ci/ft^3$ (4×10^{-4} $\mu Ci/cm^3$).

PURGING OF RADIOACTIVITY FROM CHIMNEY

As gas is flared from the chimney, "clean" gas from the surrounding formation will flow into the chimney to decrease concentrations of radionuclides in the chimney gas. Two models are available for predicting the reduction of radionuclide concentrations as gas is flared; the simplest assumes that as fresh gas enters the chimney, it mixes completely and instantaneously with all the gas in the chimney. This results in predicted concentrations of radionuclides that decrease exponentially with the total volume of gas flared (17).

The other model, developed by Higgins, et. al. (17), assumes that no mixing takes place and that the fresh gas displaces the radioactive gas in a piston-like fashion. In this case, concentrations of radionuclides in the flared gas would remain constant at early times, decrease rapidly at intermediate times, and finally go to zero after flaring at most four to five chimney volumes (NTP) of gas.

The actual decrease of radioactivity probably will not correspond precisely to either model but will lie somewhere between the two predictions. Higgins, et. al., indicate that measurements of Gasbuggy ^{85}Kr concentrations were constant at early times, conforming to the no-mixing model (18). A conservative approach would be to assume that concentrations will remain constant until approximately 0.1 to 0.2 chimney volumes have been flared (conforming to the no-mixing model) and will then decrease exponentially with the volume of gas flared (perfect-mixing model).

APPENDIX D

RADIOACTIVITY IN GROUND WATER

Little information is available concerning occurrence and movement of ground water or magnitudes of hydraulic gradients existing in the Mesaverde Formation near the Rulison chimney. The USGS indicates that usable ground water in the Rulison area is primarily limited to alluvium and terrace deposits, and that underlying bedrock formations are generally impermeable and yield little water. From observations made during the drilling of the exploratory hole R-EX, the USGS concluded that little mobile water occurs in the formations penetrated by the hole (11). However, the USGS also reports that the Ohio Creek Conglomerate has yielded water in other gas wells drilled in the Rulison field and that some water was found in a sandstone lens in the upper Mesaverde Formation (11). There presently seems to be insufficient evidence for concluding that mobile water cannot be present in the fracture zone surrounding the chimney.

The Mesaverde Formation consists of sandstone lenses interbedded with shales of much lower permeabilities (10,11). Permeabilities of the shales might reasonably be expected to be two orders of magnitude lower than the permeabilities of the sandstone lenses (16). Average sandstone lens porosity and water saturation for the Rulison field are given as 9.7 per cent and 45 per cent, respectively (10). Ground water movement in such unsaturated media is typically much slower than movement in saturated media. Capillary forces and other factors affect moisture movement in unsaturated media. Prediction of moisture movement in unsaturated media requires more data than are available for the Rulison field. However, some estimate of possible radionuclide movement is desirable. Though "worst case" estimates are often misleading, it is felt that the development of a "worst case" estimate of

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possible ground water movement near the Rulison chimney will serve to illustrate that the chances are very small that significant concentrations of radionuclides will occur at any ground water use point.

The simplest approach to a "worst case" estimate of ground water movement is to assume that fractures from the chimney will intersect a water-bearing formation and will introduce water into the chimney. Ground water velocities which would occur under the resulting saturated conditions would be much greater than velocities which would occur under unsaturated conditions. It is emphasized that radioactivity will tend to remain in place unless mobile water is present and that the assumption that water will be introduced into the chimney is therefore conservative. The observations of water in the Ohio Creek Conglomerate at other locations and in a sandstone lens in the upper Mesaverde Formation partially justify the assumption that the fracture system will contact an aquifer.

There is no means of estimating how much water will be present. Therefore it will be arbitrarily assumed that all radioactivity from the detonation will be uniformly mixed with a volume of water equivalent to the void volume of the chimney (2.1×10^6 ft^3). Using these assumptions and the estimated tritium production given in Table 1, the resulting tritium concentration can be estimated as 0.17 μCi/ml, about 170 times the concentration guides given by the AEC Manual, Chapter 0524 (39).

Initial reduction of concentrations of radionuclides such as ^{137}Cs and ^{90}Sr by ion exchange will be neglected. This assumption results in estimates of concentrations of these radionuclides which are probably conservative, regardless of the amount of water actually introduced into the chimney.

Corresponding estimated concentrations of ^{137}Cs and ^{90}Sr are 0.12 μCi/ml and 9.8×10^{-2} μCi/ml, respectively, which are 1.8×10^{4} and 1×10^{6} times the Chapter 0524 concentration guides for ^{137}Cs and ^{90}Sr, respectively.

Factors which influence the velocity of ground water movement include the degree of saturation of the pore space, the permeability of the medium, presence of fractures, and the existing hydraulic gradients. For the entire Mesaverde Formation these factors are not well-known. Characteristics of the sandstone lenses have been reported (10), but the geometry of these lenses is not known. Conservative assumptions must therefore be made to permit estimation of ground water movement.

It will be assumed that the entire formation has the permeability of the sandstone lenses, and the presence of interbedded shales will be ignored. Saturated flow conditions will also be assumed. The Green River, Wasatch, Ohio Creek Conglomerate, and Mesaverde Formations dip to the north at about two degrees (11). In the absence of disturbances, the hydraulic gradient might be assumed to follow the dip of the formations, so that ground water flow would also follow the dip of the beds.

An expression for the average velocity (tracer velocity) of ground water flow under Darcian conditions is (23,24):

$$v = \frac{ks}{\mu n} \frac{dp}{dx} \qquad \text{Equation D-1}$$

WHERE:

v = tracer velocity, feet/second

s = specific weight of water, lbs/ft^3 = 59.8 lbs/ft^3 at 215°F.

u = viscosity of water at formation temperature.
= 0.59×10^{-5} lb-sec/ft^2

n = formation porosity.

$\frac{dp}{dx}$ = pressure gradient or hydraulic gradient, feet of water per foot of distance.

k = permeability of the saturated medium, ft^2.

The reported average permeability and porosity of the sandstone lenses of the Mesaverde Formation are 0.5 millidarcys and 8-10 per cent, respectively. Using these values in Equation D-1 and assuming the hydraulic gradient is approximately equal to the dip of the beds, the estimated groundwater velocity would be approximately 0.6 ft/year. This development assumes saturated flow conditions. The conservative assumptions leading to this estimated movement should be emphasized. The first assumption is that relative large amounts of water will be introduced into the chimney from some overlying aquifer, resulting in saturated flow through the Mesaverde Formation away from the chimney. It is also assumed that the entire Mesaverde Formation has the permeability reported for the sandstone lenses, which may be conservative by two orders of magnitude. It is implicitly assumed that the wetting front of the flow from the chimney will move at saturated flow velocities, also a conservative assumption.

Ignoring dilution by diffusion and mixing, tritium would be reduced to the AEC concentration guide of 1×10^{-3} μCi/ml by radioactive decay in about 7.4 half-lives. Since tritium moves with the velocity of ground water flow, tritium might move a very few feet before decaying to the concentration guide. Even at 200 times the conservative estimate of ground water velocities, tritium would still move less than three miles before being reduced to the concentration guide.

Tritium can be assumed to move with the velocity of ground water, but the movement of ^{137}Cs and ^{90}Sr will be retarded by ion exchange with the medium. The degree of retardation can be predicted from a property of the medium called the distribution coefficient, K_d. Values of K_d for rocks in the Rulison area were not measured, but Isotopes, Inc. has reported values for sandstones near the Gasbuggy detonation as approximately 100 and 1.4 for ^{137}Cs and ^{90}Sr, respectively (15). These values will be assumed to be representative of the Mesaverde Formation also. CER Geonuclear reported an average overburden density of 2.35 g/cm^3 and a core grain density of 2.67 g/cm^3 for the Rulison site (10), but the density of the sandstone may be somewhat greater than the average. A value of 2.4 g/cm^3 for the bulk density appears to be a reasonable assumption.

The relationship between the average ground water velocity, v, and the effective velocity, v', of a given radionuclide in ground water is (24)

$$\frac{v'}{v} = \frac{1}{1 + K_d(m/n)} \qquad \text{Equation D-2}$$

WHERE:

k_d = distribution coefficient for the particular radionuclide in a given medium, ml/g.

m = bulk density of the rock or aquifer, g/cm^3.

Using the above values for bulk density and K_d,

$$v'/v = 4.2 \times 10^{-3} \text{ for } ^{137}Cs$$

$$v'/v = 0.029 \text{ for Sr-90}$$

Ignoring dilution by diffusion and mixing, ^{137}Cs and ^{90}Sr would be reduced to their appropriate AEC concentration guides in about 14 half-lives and 20 half-lives, respectively. Thus, both would decay to the concentration guides before moving more than a few feet. At 200 times the conservative estimate of ground water velocity, ^{90}Sr might move about one-half mile before decaying to its concentration guide. While gas is being released from the well, hydraulic gradients in the formation surrounding the chimney will drive water toward the chimney because chimney pressures will be lower than the pore pressure of the formation. Until gas production from the well ceases, no migration of radioactivity away from the chimney is expected.

The analysis presented above cannot be construed as an accurate picture of the movement of radioactivity in ground water, since the estimates given result from assuming a very unlikely "worst case." However, the estimates serve to illustrate that transport of radioactivity from the Rulison chimney to any ground water use point is highly improbable.

APPENDIX E

METEOROLOGY AND DIFFUSION

Climatological Data

This section summarizes climatological data needed to estimate environmental effects of production testing. Local meteorology is strongly affected by terrain features. The area can best be described as a large plateau sub-divided into mesas by drainage channels. The important features are:

1. Battlement Mesa - The Rulison site is located on the north side of the mesa, which slopes generally from SE to NW.

2. Morrisania Mesa - located below the Rulison site on the northern slope of Battlement Mesa.

3. Battlement Creek and its associated valley - The valley passes near the Rulison site, sloping generally south to north, and cuts across Morrisania Mesa to reach the Colorado River. This valley creates the local wind regime (drainage and upslope) for the Rulison site. The valley is about 1,000 feet deep.

4. Colorado River and its associated valley - The river runs generally from NE to SW, passing about six miles north of the site. Battlement Mesa and Morrisania Mesa form the valley walls to the south and the Roan Cliffs form the valley wall to the north.

Important terrain features are indicated schematically in Figure 3 of the text. Elevations on the figure are given in thousands of feet above mean sea level (1 K = 1,000 ft).

Three prevailing wind regimes are indicated on the figure.*

Nightly drainage winds blowing toward the NNW and daily upslope winds toward the SSE in the Battlement Creek valley form one wind regime. These winds probably build up to about 1,000 feet above the valley floor.*

Valley flow in the Colorado River Valley directly north of the site, which generally flows east-west, forms another wind regime. The mixing depth for this valley is not well-known but has been noted to build up to around 1500 ft or more (over Morrisania Mesa).

Regional gradient flow above the topographical features is generally toward the ENE. Although this wind information is based on air soundings at Grand Junction (elevation 4820 feet), measurements taken at about 10,000 feet on Battlement Mesa are similar. The 500-mb** wind rose (18,500 feet) from Grand Junction is similar, but the prevailing wind direction is toward the east and wind speeds are greater than those at the 700-mb level.

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*Meteorological data presented in this section are based on References 6 and 7 and on private conversations with personnel of ESSA/ARL.

**mb-millibar--1,000 mb is equivalent to 29.53 inches of mercury.

Diffusion Estimates

There are numerous equations for estimating plume rise and atmospheric diffusion. Equations for plume rise are usually based on empirical data or dimensional analysis. Briggs' equation (8) was used on recommendations of personnel from ESSA/ARL and the experience with Project Rover reactor tests at NRDS (felt to be a good analogy).* Briggs' equation is based on dimensional analysis and incorporates an empirically derived constant (Equation E-1).

Gifford's modification of Pasquill's diffusion equation is used (9) to estimate dispersion with distance. The model is generally known as the Gaussian model because of its inherent assumption of a Gaussian-shaped cloud.

Calculations for the plume rise (also referred to as effective stack height) and downwind dispersion are given at the end of this appendix. The results of these calculations are indicated in Figures E-1 and E-2.

Each figure represents a different set of conditions. Figure E-1 is based on an assumed effective stack height of 2700 feet and transport by the regional (aloft) winds, whereas Figure E-2 is based on an assumed effective stack height of only 1,000 feet and transport by the local valley winds.

This latter case (involving drainage winds) is unlikely since thermal energy will probably cause a significant fraction of the plume to rise above the terrain. It could occur during a strong inversion (causing limited plume rise) or at lower flaring rates (since plume rise is proportional to the cube root of the energy and thus flaring rate). Should the

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*Recommendation of Mr. N. Kennedy, ESSA/ARL, Las Vegas.

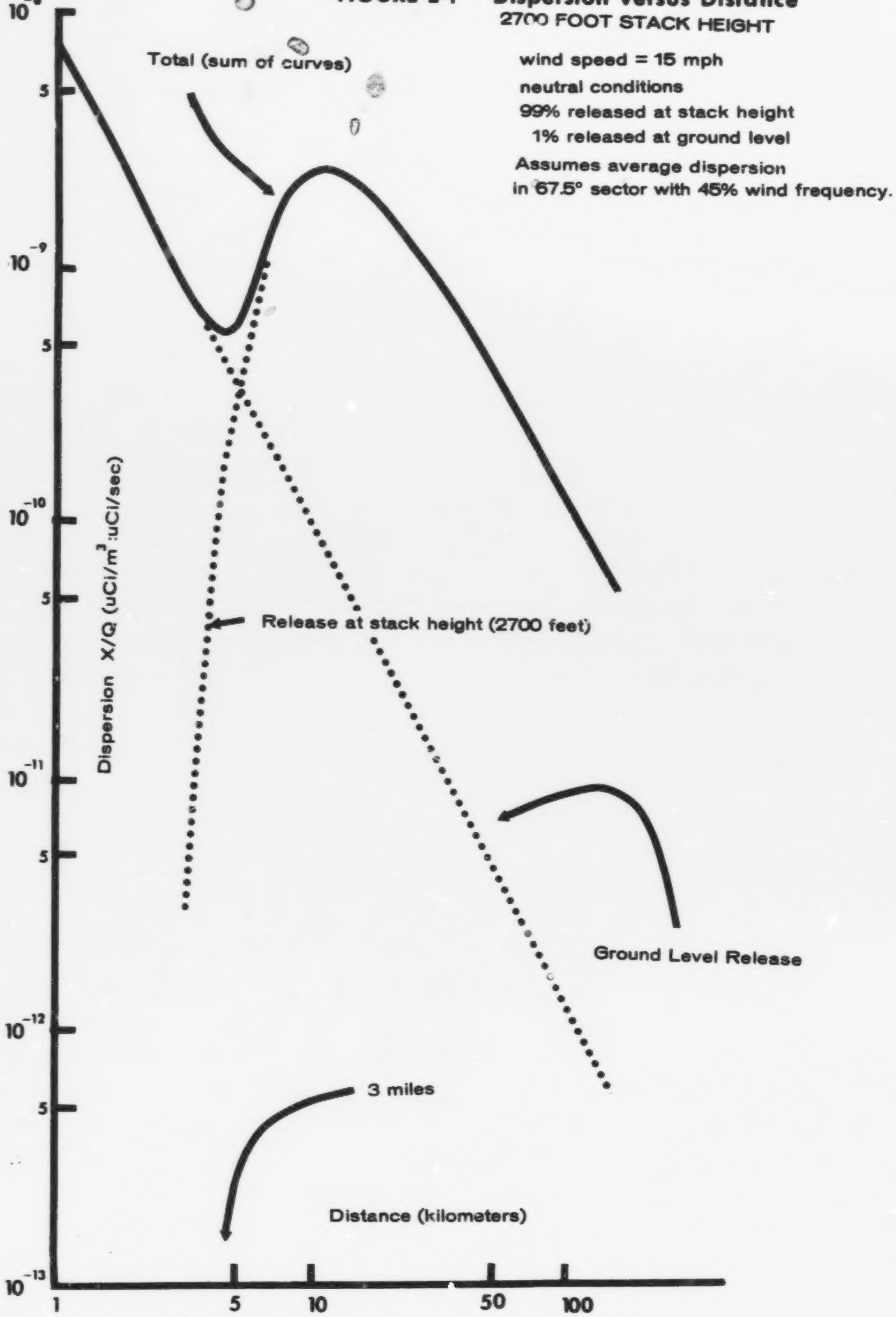

FIGURE E-1 Dispersion versus Distance

2700 FOOT STACK HEIGHT

wind speed = 15 mph

neutral conditions

99% released at stack height

1% released at ground level

Assumes average dispersion in 67.5° sector with 45% wind frequency.

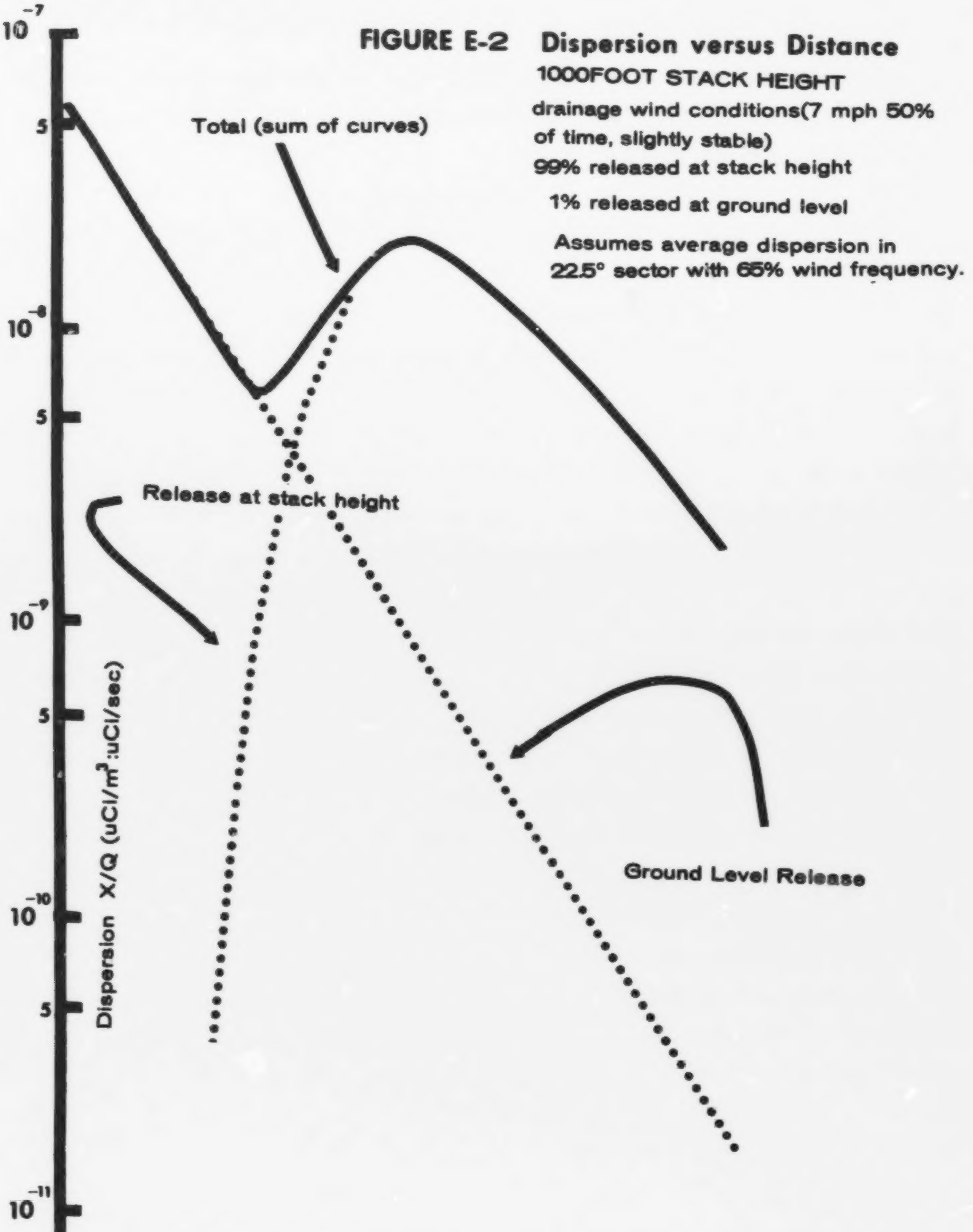

FIGURE E-2 Dispersion versus Distance

1000FOOT STACK HEIGHT

drainage wind conditions(7 mph 50% of time, slightly stable)

99% released at stack height

1% released at ground level

Assumes average dispersion in 22.5° sector with 65% wind frequency.

"inversion case" occur, the effluent might be caught in the inversion and possibly not be transported to the ground until the inversion broke up.

For both dispersion calculations, 0.01 of the source was assumed to be released on the ground and the remaining 0.99 at the effective stack height. This assumption is based on empirical analysis of the previously mentioned NRDS work. This concept does not really imply release from two points but rather a "peeling-off" of part of the effluent during the plume rise. Thus, even if the estimated effective stack height of about 3,000 feet is correct, some of the effluent will probably follow the valley drainage winds.

The dispersion curves in Figures E-1 and E-2 are based on idealized topography (flat plains) and assumptions concerning transport winds such as the fraction of the effluent released at each altitude. Uncertainties caused by the complicated terrain and uncertainties in wind parameters throw doubt on the accuracy of estimates of the variation of downwind concentrations with distance. Therefore, a constant dispersion coefficient, 3×10^{-9} sec/m^3, will be assumed for distances beyond three miles, the distance of the population closest to the site. This assumes the conditions of Figure E-1 are more representative of the long-term average than those of Figure E-2.

It is felt that

- a small fraction of the effluent will be caught in the Battlement Creek Valley flow;
- at high flaring rates, the majority of the effluent will rise above the terrain to be transported by the regional winds.

ATMOSPHERIC DISPERSION CALCULATIONS

EFFECTIVE STACK HEIGHT - PLUME RISE. (From Reference 8)

$\Delta h = 1.6\ F^{1/3}U^{-1}X^{2/3}$ (Briggs' Equation) E-1

WHERE:

Δh = the effective plume rise due to thermal buoyancy above the stack in feet. For an effluent with high thermal energy, thermal buoyancy is the dominant factor and the momentum or jet rise is negligible.

1.6 = Constant for fit of empirical data.

F = Flux of buoyancy force from stack, divided by π and the mean atmospheric density - $4.3 \times 10^{-3}\ Q_H$. The coefficient varies inversely with atmospheric pressure. A value of 3.18×10^{-3} was used for Rulison (8200 ft MSL). $Q_H \equiv$ cal/sec and $F \equiv \text{ft}^4/\text{sec}^3$.

U = Mean wind speed = 7 mph = 10.3 ft/sec

X = Distance downwind from the stack. Used 5280 ft (based on experience from NRDS).

$F = 3.18 \times 10^{-3}\ Q_H$

$Q_H = 2 \times 10^7\ \text{ft}^3/\text{day} \times (1{,}000\ \text{Btu}/\text{ft}^3$ natural gas)

$(252\ \text{cal}/\text{Btu}) \times (\text{day}/8.64 \times 10^4\ \text{sec})$

$Q_H = 5.82 \times 10^7$ cal/sec

$F = 3.18 \times 10^{-3} \times 5.82 \times 10^7 = 1.86 \times 10^5\ \text{ft}^4/\text{sec}^3$

$$\Delta h = 1.6\ F^{1/3}\ U^{-1}\ X^{2/3}$$

$$= 1.6\ (1.86 \times 10^{5}\ ft^{4} sec^{-3})^{1/3} (10.3\ ft\ sec^{-1})^{-1} (5280\ ft)^{2/3}$$

Units - $ft^{4/3}\ sec^{-1}\ ft^{-1} sec^{1} ft^{2/3} = ft$

$$= 1.6 \times 57.1 \times 10.3^{-1} \times 301$$

$$= \underline{\underline{2700\ ft}}$$

ATMOSPHERIC DISPERSION (Reference 9)

There are numerous approaches for estimating downwind concentrations from releases. The most common is to estimate short-term average (3-minute) concentrations along the centerline of the plume (Equation E-2). It was felt that a more representative value in this case would be the cross-wind average for the sector of concern (Equation E-3). Equation E-3 was used to calculate cross-wind average air concentrations based on the prevailing wind sector and the probability for winds blowing into that sector.

The basic equation for describing the short-term average ground level downwind concentration from a continuous point source is:

$$X = \frac{Q}{\pi \sigma_y \sigma_z U} \exp\left[-1/2 \left(\frac{\Delta h}{\sigma_z}\right)^2 \right] \qquad \text{(page 6, Ref. 9)} \quad E-2$$

WHERE:

X = Downwind concentration in units of release/m^3.

Q = Source term in units/sec.

σ_y & σ_z = Cross wind and vertical dispersion coefficients respectively (meters).

U = Wind speed (meters/sec)

exp[ ]: Indicates e raised to the power inside the brackets.

Δh = Plume rise

The ground-level crosswind-integrated concentration is given by:

$$X_{cwI} = \frac{2Q}{\sqrt{2\pi}\,\sigma_z\,U} \exp\left[-1/2 \left(\frac{\Delta h}{\sigma_z}\right)^2\right] \qquad \text{E-3}$$

WHERE:

X_{cwI} = The cross-wind integrated concentration in (units/m^3) x m or units/m^2.

The other symbols are as previously defined.

To obtain the concentration within a sector, the equation is multiplied by the frequency f and divided by the arc at the distance of interest $2\pi X\theta$.

WHERE:

X = distance downwind in meters.

θ = fraction of the 360° arc being considered (e.g., if 60°, then $\theta = 1/6$).

The source is considered to be composed of two releases; (1) 0.01 of the total released at the surface, and (2) 0.99 released at the height of rise of the plume.

Two wind regimes were considered: (1) valley flow with Δh = 1,000 feet, and (2) Δh = 2700 feet and transport by the "aloft" or regional winds.

The following illustrates the calculation for the concentration (Δh = 2700 ft) at 10 km or 6.2 miles downwind assuming the regional wind regime prevails, and ignoring topography effects (X_{cwI} becomes X_{Ave} to indicate the concentration averaged cross-wind).

$$X_{Ave} = \frac{2Q}{\sqrt{2\pi}\ \sigma_z U} \frac{f}{2\pi X\theta} \exp\left[-1/2 \left(\frac{\Delta h}{\sigma_z}\right)^2\right]$$

Q = 0.99 unit μCi/sec at Δh; 0.01 at surface

U = 15 mph = 6.72 m/sec

X = 10 km

θ = (67.5°/360°)
$2\pi X\theta = 2\pi\ 10^4\ (67.5/360) = 1.18 \times 10^4$ m

f = 0.45

Δh = 2700 ft = 822 meters

σ_z = (C, neutral) = 5×10^2

$$\chi_{cwI} = \frac{2 \times 0.99}{\sqrt{2\pi}\ 5 \times 10^2 \times 6.72}\ \frac{0.45}{1.18 \times 10^4} \exp\left[-1/2\ \left(\frac{822}{500}\right)^2\right]$$

$$= 2.34 \times 10^{-4}\ \ 3.82 \times 10^{-5} \exp\left[-1.3\right]$$

$$= \underline{\underline{2.4 \times 10^{-9}\ \mu Ci/m^3 : \mu Ci/sec}} \quad \text{(67.5° average)}$$

APPENDIX F

TRITIUM DOSE CALCULATION

$$\text{Dose} = \frac{\mu\text{Ci intake}}{\text{g of tissue}} \times \frac{3.7 \times 10^{4}\text{d}}{\mu\text{Ci-sec}} \times \frac{0.01 \text{ Mev}}{\text{d rad/rem}} \, \frac{1.6\text{x}10^{-6}\text{ergs}}{\text{Mev}} \, \frac{\text{rad-g}}{100 \text{ erg}} \times$$

$$\frac{8.64 \times 10^{5} \text{ sec}}{0.693} = \text{rem}$$

WHERE:

μCi intake - is the quantity ingested or inhaled.
g of tissue - whole body mass; 7×10^{4}g for an adult, or 10^{4}g for an infant (33,40).
0.01 Mev - effective energy for tritium (32,33).
$8.64\text{x}10^{5}$sec - effective biological half-life of tritium for adults; 10 days (32).

For an adult this gives:

1.06×10^{-4} rem per μCi intake

Infant:

ICRP has not specified a biological effective half-life for tritium in an infant, but, considering the relative body masses and daily liquid intake of an adult and infant, it appears that the effective half-life in an infant would be much shorter than for an adult. Assuming a liter per day liquid intake and 10 kg body mass, the intake equals the body mass after one adult effective half-life (10 days).

The following is proposed as an estimate for the effective biological half-life for an infant:

Assume:

a. Tritium is primarily associated with the body water.

b. The body water is relatively the same fraction of total mass in an infant as in an adult. Thus, the effective half-life for an infant can be scaled to that for an adult by using the analogy of a tank mixing model.

The concentration in a tank at t=0, where the inflow equals the outflow and the inflow concentration is zero can be expressed by the following equation:

$$K(t) = K_o \exp{-C(Q/W)t}$$

WHERE:

$K(t)$ is the concentration at time t.

K_o is the concentration at time $t = 0$.

C is a constant to compensate for non-ideal mixing.

Q is the inflow rate, or human consumption.

W is the tank volume, or human body mass.

The combination of the parameters $C(Q/W)$ are analogous to an effective decay constant. Assuming C is essentially the same for both an infant and an adult (assumptions a and b above), the infant effective half-life may be scaled from the adult effective half-life by the ratio of the decay constants:

$$\begin{pmatrix}\text{Adult effective}\\ \text{half-life}\end{pmatrix} \times \frac{C_a(Q_a/W_a)}{C_i(Q_i/W_i)} = \begin{matrix}\text{Infant effective}\\ \text{half-life}\end{matrix}$$

Using the following values:

$C_i = C_a$
Q_i and Q_a are 1 and 2.2 liters per day respectively.
W_i and W_a are 10 and 70 kg respectively.

Therefore:

$$(10\ \text{days})\left(\frac{2.2\ \text{l/day}}{70\ \text{kg}} \Big/ \frac{1\ \text{l/day}}{10\ \text{kg}}\right) = 3.1\ \text{days}\ \begin{matrix}\text{Infant bio-}\\ \text{logical}\\ \text{effective}\\ \text{half-life}\end{matrix}$$

For a 10 kg infant:

$\underline{2.3 \times 10^{-4}\ \text{rem per}\ \mu\text{Ci intake}}$

The following indicates the derivation of the dose conversion parameter for tritium concentration in μCi/ml of body water (hydrogen equivalent) integrated over a period of days i.e., (μCi/ml) x days).

$$\frac{\mu\text{Ci-day}}{\text{ml of water}} \times \frac{3.7\text{x}10^4\text{d}}{\mu\text{Ci-sec}} \times \frac{0.01\ \text{Mev-rem*}}{\text{d-rad}} \times \frac{1.6 \times 10^{-6}\text{ergs}}{\text{Mev}} \times \frac{\text{rad-g}}{100\ \text{ergs}} \times$$

$$\frac{6.3\text{x}10^4\text{g (H equivalent water/total body)*}}{7\text{x}10^4\ \text{g/total body*}} \times \frac{8.64\text{x}10^4\text{sec}}{\text{day}} =$$

$$\underline{\frac{0.46\ \text{rem}}{\mu\text{Ci-day/ml}}}$$

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*Reference 33.

APPENDIX G
KRYPTON-85 DOSE CALCULATIONS

Cloud Submersion Dose (Ref. 33 and 34)

Assumptions:

1. Spherical cloud of uniform concentration. The cloud is considered to be spherical and infinite with respect to the range of the beta particles.

2. The receptor volume does not perturb the radiation field.

3. Any ^{85}Kr in the lungs or dissolved in the body fat is compensated by assuming an infinite spherical or 4 π cloud. The ICRP (Ref. 33) assumes a 2^{π} cloud.

Given:

1. ^{85}Kr effective energy 0.24 Mev

2. Temperature - 50° F, pressure 750 mb

$$D(\text{rem/sec}) = \frac{E(\text{Mev})\ 1.6 \times 10^{-6}(\text{ergs/Mev})3.7 \times 10^{10}(\text{d/Ci-sec})(\text{Ci/m}^3)}{1293(\text{density of air-g/m}^3)100(\text{ergs/g-rad})(\text{rad/rem})}$$

$$= 0.457\ EX$$

Adjusting the constant for the ambient air conditions, and changing the dose rate to rems per day--

$$D(\mathrm{rem/day}) = 5.5 \times 10^{4}\ E(\mathrm{Mev}) \times (\mathrm{Ci/m^{3}})$$

$$= 5.5 \times 10^{4} \times 0.24 \times 2.5 \times 10^{-12}$$

$$\text{Dose} = 3 \times 10^{-8}\ \mathrm{rem/day}$$

APPENDIX H

SUMMARY OF PARAMETERS FROM NVO-61 (38)

Rulison Cavity (H+180 days)

Parameter	NVO-61	This Report
Cavity Void Volume (ft^3)	3.05×10^6	2.15×10^6
Cracking radius (ft)	485	370
Cavity radius (ft)	90	80
Cavity pressure (psia)	2,940	2,640
Cavity temperature (°F)	375	380

Flaring Schedule and Parameters

Parameter	NVO-61	This Report
High rate flow test (ft^3/day)[a]	2×10^7	2×10^7
Duration	3 3-day	
Intermediate flow test[a] (ft^3/day)	5×10^6	
Duration	2 months	
Long term production (ft^3/day)[a]	5×10^6	
Duration	6-8 months	

[a] Indicated as maximum flow rates

Cavity Inventory of Radionuclides (H+180 days)

Nuclide	NVO-61 Curies	This Report Curies
^{85}Kr	9.6×10^2	9.6×10^2
^{90}Sr	5.9×10^3	5.9×10^3
^{137}Cs	7.5×10^3	7.5×10^3
^3H	$10^3 - 10^4$	10^4
^{14}C	0.01-0.1	
^{37}A	10 - 100	
^{39}A	2 - 20	

Radionuclide Concentration In Gas (H+180 days)

Nuclide	NVO-61[b] $\mu Ci/cm^3$	This Report $\mu Ci/cm^3$
^3H	$0.8 - 8 \times 10^{-4}$	$0.07 - 1.5 \times 10^{-3}$
^{85}Kr	8×10^{-5}	1.4×10^{-4}

[b] Based on cavity gas volume of $1.27 \times 10^7 m^3$ corrected to 10.8 psi and 0° C (4.55×10^8 ft^3); this report 2.4×10^8 ft^3 (NTP).

Dose Estimates

Dose Pathway	NVO-61[c] Max. Credible Dose (mrem)	Estimates in this Report[d] (mrem)
Inhalation Adult (at 2 miles)	0.3	10^{-3}
Food Chain	4 - 100	Conservative Estimate 3 Expected 0.1

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[c] Based on maximum credible accident type approach. It was assumed 94% of the gaseous radioactivity (primarily tritium and ^{85}Kr) was released in a 24-hour period.

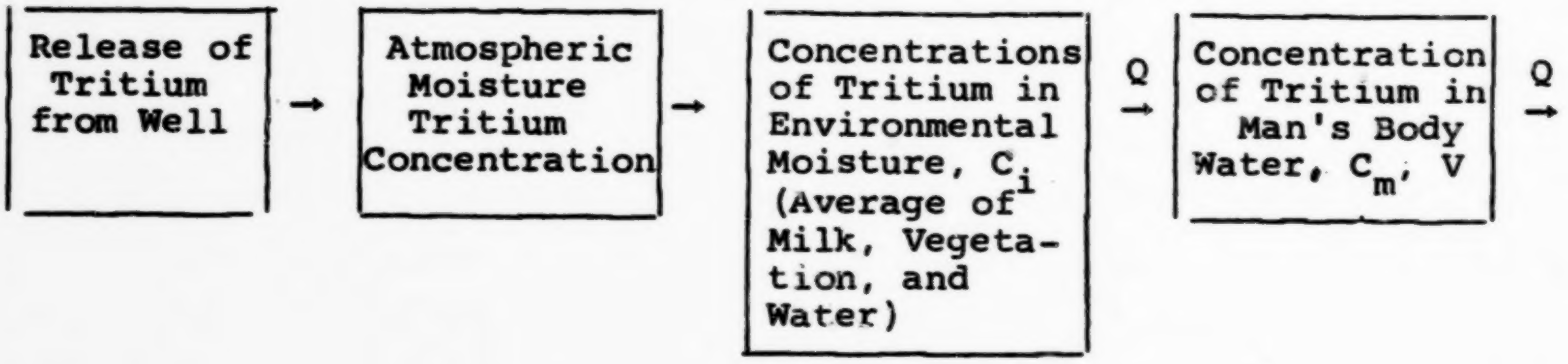
[d] This calculation was based on flaring at 20 x 10^6 ft^3/day for 10 days. Two thirds of the tritium and ^{85}Kr in the cavity are assumed to be released during this period.

APPENDIX I

ACUTE AND CHRONIC DOSES FROM INGESTION OF TRITIUM

FIGURE I-1

TRITIUM INGESTION MODEL


Release of Tritium from Well
Atmospheric Moisture Tritium Concentration
Concentrations of Tritium in Environmental Moisture, C_i (Average of Milk, Vegetation, and Water)
Q
Concentration of Tritium in Man's Body Water, C_m, V
Q

WHERE:

Q - Volume of intake and excretion of water by man; 2.2 l/day.

C_i - Tritium concentration in man's intake water.

C_m - Tritium concentration in man's body water.

V - Volume of man's body water; water equivalent of total hydrogen.

Figure I-1 indicates the model used to describe the exposure of man to tritium by the ingestion pathway.

Methods are available for predicting atmospheric concentrations which are likely to result from flaring natural gas from the well head. Presence of tritium in the atmosphere will result in uptake of tritium by vegetation but insufficient data are available to directly convert atmospheric tritium levels to the corresponding levels in vegetation moisture. Consequently experience from Gasbuggy will be used to estimate tritium levels in vegetation. As discussed in the text, the highest concentration of tritium in vegetation moisture observed during environmental sampling for Project Gasbuggy was 36 pCi/ml of moisture. Allowing for both a conservative assumption of higher levels of tritium in flared gas from Rulison (42 $\mu Ci/ft^3$ as compared with 18 $\mu Ci/ft^3$ from Gasbuggy) and the higher expected volumes of flared gas (20 million cubic feet per day from Rulison as opposed to 5 million cubic feet per day from Gasbuggy), it is assumed that peak levels of tritium in vegetation moisture might range up to a factor of ten greater than occurred with Gasbuggy. The assumed maximum level in vegetation moisture might then be 360 pCi/ml of moisture. Based on information in the text, it is assumed that the concentrations of tritium in milk and water will be 36 and 1 pCi/l respectively.

Assuming a daily human intake of 2.2 liters per day of moisture composed of 200 ml of vegetation moisture, 1,000 ml of milk, and 1,000 ml of water, the highest expected weighted average tritium concentration of the total daily intake would then be about 50 pCi/ml (360 x 200/2200+ 36 x 1000/2200 + 1 x 1000/2200 = 50). The majority of this is from vegetation, about 1/3 is from milk, and the contribution from water is over an order of magnitude less than the vegetation and milk fraction.

In order to calculate possible internal doses from tritium ingestion, three simplifying, conservative assumptions will be made. Assume first that tritium levels in vegetation moisture equilibrate essentially instantaneously at the peak level of 360 pCi/ml as soon as high-rate flaring begins. Next assume that tritium levels in milk rise and fall with tritium levels in vegetation moisture without any delay. Tritium levels in milk therefore are assumed to equilibrate at 36 pCi/ml as soon as high-rate flaring begins. Also assume that the levels of tritium in vegetation moisture remain constant at the peak value of 360 pCi/ml throughout the three-week high-rate flaring period and then decay exponentially with an 85-day half-life. The following indicates the reasoning used in selecting this value:

Tritium Environmental Half-Life

The assumption of an 85-day effective half-life is based on the following information:

1. The effective half-life for tritium observed for the previously mentioned sample from Gasbuggy (peak 36 pCi/ml of water in vegetation) was 85 days (two results with an increment of time of 260 days).

2. Preliminary information from Schooner for a high desert environment (about 5,000 ft MSL) indicated values of 70-100 days for desert plants such as Mormon Tea and Galleta Grass. The 70-100 day half-life occurred subsequent to shorter half-lifes within the first several months after deposition. A 10-day half-life accounted for about 3/4 of the total depletion*.

3. Effective half-life for tritium used in AEC evaluation; 28 days (38).

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*Personal communication with Dr. B. Mason of SWRHL (presently employed with BMI, Las Vegas, Nevada).

4. Martin, et. al. (42) indicated that the mean residence time in soil for a surface application of tritium was 37 days.

5. The ecological half-life for radionuclides deposited on vegetation is generally accepted to be about 14 days (37). This half-life is largely due to plant growth and would be longer in an arid environment.

For dry deposition, the predominant case for Rulison, the predominant vegetation uptake path should be through deposition on the vegetation. Deposition on soil and subsequent root-uptake should result in some dilution by soil water. It would appear the effective half-life of tritium in vegetation, contaminated by deposition, would be equal to or less than the ecological half-life (14 days) for other radionuclides such as ^{131}I, etc. It is difficult to evaluate the significance of tritium uptake via the soil-root pathway for the Rulison release situation and environment, but this would increase the half-life. The 85-day half-life observed for Gasbuggy probably reflects the effect of the arid environment. The Rulison environment is semi-arid. Vegetation for human or domestic animal consumption is largely irrigated, and thus the effective half-life would be less than that for Gasbuggy.

But due to the lack of specific information and in order to be reasonably conservative, a value of 85 days for the effective half-life of tritium will be used. This may be conservative by a factor of about four.

The discrepancies between these assumptions and actual physical and biological processes are obvious. Tritium will be gradually deposited on vegetation, probably reaching a peak value at the end of the high-rate flaring period. Levels of tritium in milk will be affected by the biological half-life of tritium in cows and will therefore lag behind increases in environmental levels. These assumptions result in calculated doses which are conservative*, but they allow comparison of the acute dose received during the flaring period with the chronic dose resulting from residual tritium concentrations in vegetation. More complex models could be formulated, but the data available do not justify more complex formulations.

Tritium concentrations in the human water intake and in human body water which would result from the above assumptions would vary with time as shown in Figures I-2 and I-3. The dotted line on Figure I-2 indicates the general form of expected actual variation with time of tritium levels in human water intake.

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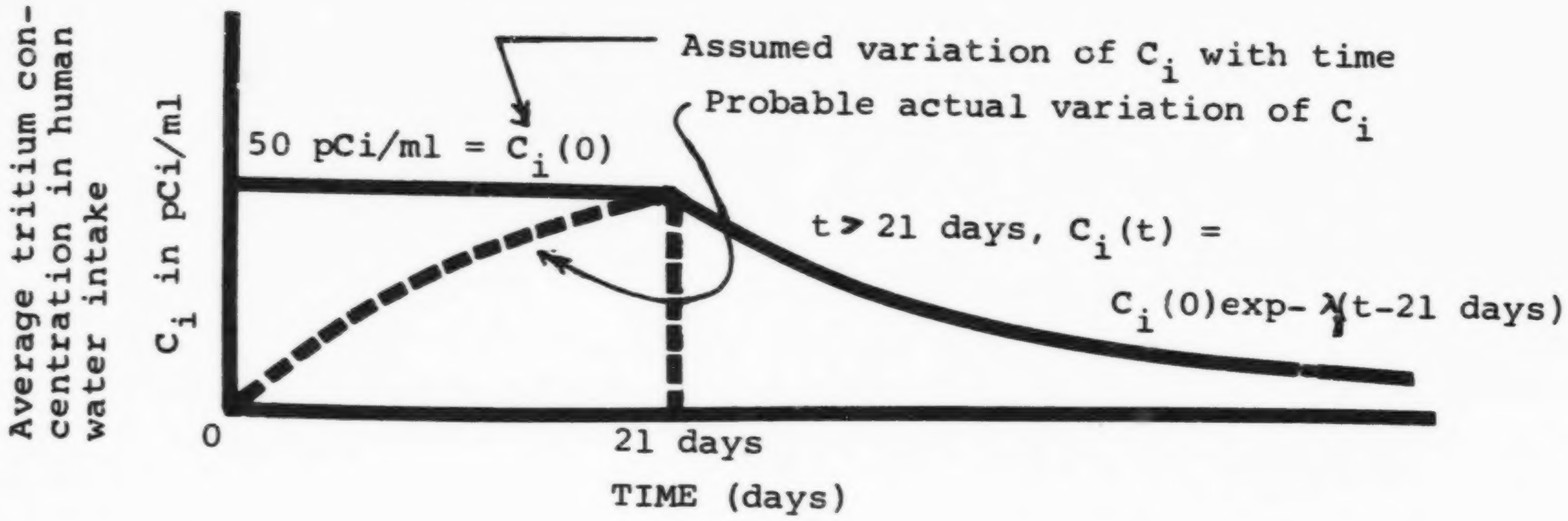
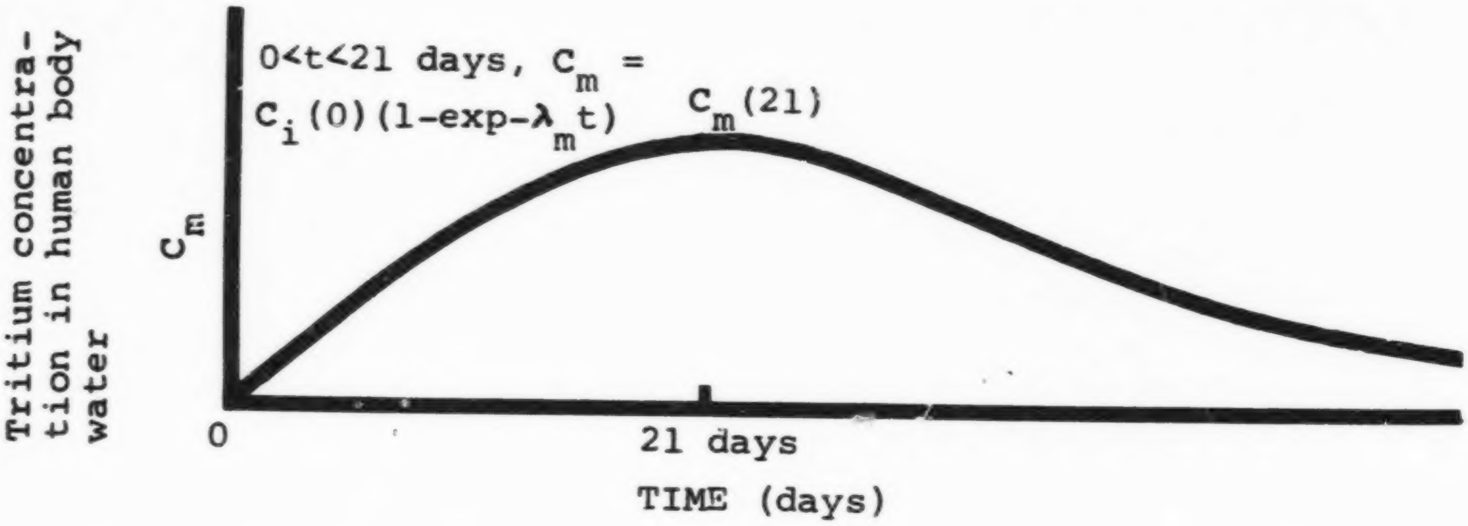
*The estimation of the acute dose may be conservative by a factor of two to three (rectangle phase in Figure I-3), but this is only a fraction of the total dose.





Using these assumptions, the tritium concentration in man's body water, C_m, during the period $0 \leq t \leq 21$ days is given by

$$C_m = C_i(0)(1-\exp-\lambda_m t) \quad . \qquad \text{Equation I-1}$$

WHERE

$$\lambda_m = \text{biological constant of tritium in man} = \frac{\ln(2)}{\text{biological half-life of tritium in man}}$$

For t>21 days, the average tritium concentration in man's intake water is given by

$$C_i = C_i(0)\exp-\lambda_i(t-21) \qquad \text{Equation I-2}$$

WHERE

λ_i = decay constant for tritium in vegetation moisture =

$$\frac{\ln(2)}{85 \text{ days}}$$

For the period t>21 days, an expression for the tritium concentration in man's body water is derived by considering the body to be a tank or reservoir in which the intake water is assumed to be completely and instantaneously mixed. Where Q is the intake water (2.2 liters/day) and V is the volume of body water (water equivalent of hydrogen), an activity or mass balance of the tritium flow through the body results in the differential equation

$$(Q/V)(C_m - C_i) + \frac{dC_m}{dt} = 0 \qquad \text{Equation I-3}$$

for t>21 days

This equation can be solved through normal techniques to yield

$$C_m(t_1) = \frac{(Q/V)C_i(0)}{(Q/V)-\lambda_i}\left[\exp-\lambda_i t_1 - \exp-t_1(Q/V)\right] +$$

$$C_m(21 \text{ days}) \exp-t_1(Q/V) \qquad \text{Equation I-4}$$

WHERE

t_1 = t-21 days

C_m(21 days) = level of tritium in body water at the end of the three-week high-rate flaring period.

The quantity (Q/V) in Equation I-4 is equivalent to a biological constant. If values of Q=2.2 liters/day and V =

63 liters are substituted to calculate the corresponding biological half-life, the value 13.5 days results. The development above assumes that tritium interacts only with water, but tritium in the body is also associated with hydrocarbons in food and is excreted with solids as well as with liquids, resulting in a biological half-life of 10 days (32). Substituting $(Q/V) = \lambda_m = \frac{\ln(2)}{10\text{ days}}$ in Equation I-4 simplifies to

$$C_m(t_1) = \frac{\lambda_m C_i(0)}{\lambda_m - \lambda_i}\left[\exp{-\lambda_i t_1} - \exp{-\lambda_m t_1}\right] +$$

$$C_m(21\text{ days})\exp{-\lambda_m t_1} \qquad \text{Equation I-5}$$

The internal dose resulting from tritium in body water can be calculated by integrating C_m over the period of interest and multiplying the result (in units of pCi-days/ml) by an appropriate dose conversion factor (4.6 x 10^{-4} millirem/day)/pCi/ml)*. It is of interest to compute the dose received during the high-rate flaring period from t = 0 through t = 21 days (the "acute" dose) and compare it with the dose received from residual tritium left in vegetation moisture after the end of the high-rate period (the "chronic" dose).

Using $C_i(0) = 50$ pCi/ml and $\lambda_m = \frac{\ln(2)}{10\text{ days}} = 0.0693\text{ days}^{-1}$ and integrating Equation I-1, the "acute" dose received during the first 21 days is estimated to be about 0.2 millirem. Using $\lambda_i = \frac{\ln(2)}{85\text{ days}} = 0.0231\text{ days}^{-1}$ and integrating Equation I-5, the "chronic" dose received from t = 21 days to infinity is estimated to be about 3 millirem. The important conclusion of this exercise is that the "chronic" dose is more than an order of magnitude greater than the "acute" dose.

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*Derived in Appendix F.